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HANDBOOK OF SOLAR ENERGY EXPERIMENTS

Prepared for

MONTANA DEPAPTMENT of NATURAL RESOURCES and CONSERVATION

HANDBOOK OF SOLAR ENERGY EXPERIMENTS

Prepared by

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Prepared for

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HANDBOOK OF
SOLAR ENERGY EXPERIMENTS

by

Charless W. Fowlkes, Ph.D.

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John Yellott generously shared his experience concerning the use of silicon cells to measure solar radiation during the inception phase of this program.

The high school students, teachers, and administrators are acknowledged for their cooperation and participation with the SIMM program. Their continued support is crucial to the success of the program.

Sketches in the first edition of this handbook were done by Terry Ferguson who also typed the manuscript and made helpful editorial comments. Pat Sullivan was responsible for typing this second revision and made helpful editorial comments. Dan Rasky performed test runs on the new experiments in the second edition.

Prof. John Drumheller and Prof. Larry Kirkpatrick of the MSU Physics Department reviewed the rough draft of the second edition and made numerous helpful suggestions and corrections.

Notes on third printing, 1981

Five years have passed since the first printing of this Handbook. During this interval there has been an explosive growth in both the technical and popular literature of solar energy utilization.

Persons currently using the Handbook should make use of this supplementary material. The physical concepts and facts presented in the Handbook remain valid. Further information on solar radiation and solar utilization is presented in the Montana Solar Data Manual which is available from DNR&C.

Background

In the Spring of 1976 Fowlkes Engineering outlined a plan for measuring the solar energy at a number of towns and cities throughout the state of Montana. The plan was submitted in the form of a proposal to DNR&C and was funded in November, 1976. The program is called SIMM (Solar Insolation Measurement, Montana).

Public high schools were selected as SIMM measurement stations, which reduced the cost of securing the solar energy data and opened oppportunities for teacher and student participation. Larry Thomas, formerly Science/Mathematics Supervisor from the Department of Public Instruction, was instrumental in setting up communication between Fowlkes Engineering and the participating high schools.

There are two types of measurement stations: automatic and manual. Thirty locations were selected for continuous, automatic solar energy recording stations. These were generally located at larger towns and placed to give uniform coverage across the state. An additional 10 manual instruments were distributed to encourage the acquisition of data in less populated areas.

The chain of events leading to your current participation in the solar energy measurement program is depicted in the diagram following. The money for this program originates in the state coal severance tax. In 1975 the Montana Legislature passed Senate Bill 86, which earmarked 2½% of the yearly coal tax revenue for research, development, and demonstration of alternative or renewable energy sources.

Coal Severance Tax

↓

Senate Bill 86, 1975
90-4-101 MCA

↓

Renewable Energy Bureau, Energy Division
Department of Natural Resources and Conservation
Renewable Energy Program

↓

Fowlkes Engineering
Solar Insolation Measurement, Montana

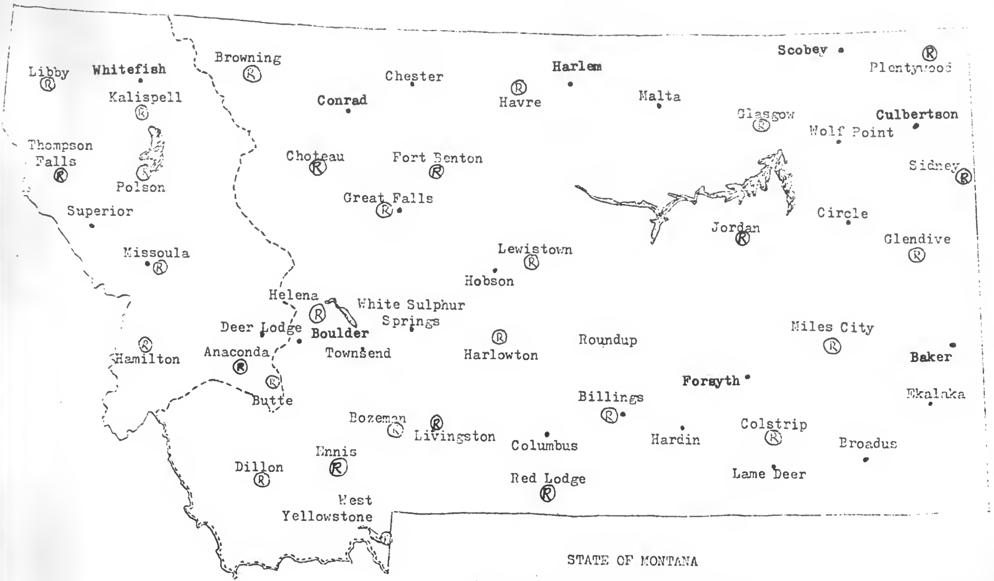
↓

Your High School
Instruments
Handbook
Participation

The Renewable Energy Program is administered by the Renewable Energy Bureau, Energy Division, Montana Department of Natural Resources and Conservation. John Orndorff is the Bureau Chief.

The manual solar energy instruments can be used in conjunction with this "Handbook of Solar Energy Experiments" to form educational units for high school science classes. This handbook will be expanded with new experiments and information as the program continues. You are encouraged to send me your comments on this handbook, as well as ideas for new experiments.

The following map shows the location of automatic solar energy measuring stations as of June 1978. Current manual measuring stations are also indicated.



STATE OF MONTANA

Ⓡ Continuous Data Recording Station
• Manual Data Stations
--- Continental Divide

Where It Starts: The Sun

Our sun is one of billions of stars in the universe. It is a sphere of very hot gaseous matter having a diameter of 1,392,000 km. The sun is, on the average, 150,000,000 km from the earth. The sketch below indicates the relative sizes of the sun and the earth and the distance between them.

o Sun 1 unit	← 100 units →	• Earth 1/100 unit

The sun derives its energy from a continuous fusion reaction within its center. This energy is transformed as it passes through to the apparent surface of the sun, or photospere. It is primarily the radiation from this photosphere that we eventually receive here on earth. The effective or average surface temperature of the sun in about 6000° K. (The actual temperatures of the gaseous layers surrounding the photosphere vary widely.)

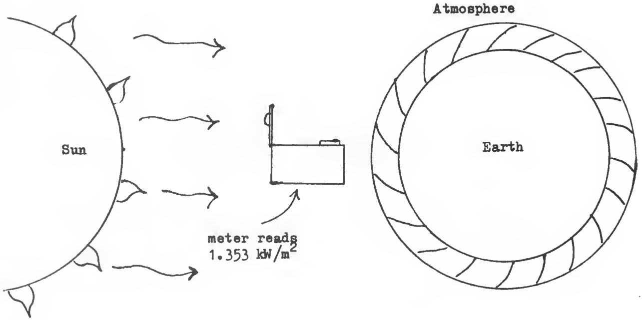
Other solar facts and estimates:

current age of sun - about 5,000,000,000 years
lifetime of sun - about another 5,000,000,000 years
sun's power output - 380,000,000,000,000,000,000,000 kW
conversion of mass into energy - 4,200,000 tonnes/second
most important fusion reaction - hydrogen to helium
temperature of center of sun - 12,000,000 to 18,000,000° K
density of center of sun - about 150 times the density of water

Back to Earth: The Solar Constant

Energy from the sun is radiated in all directions. On earth we intercept only a minute fraction of this total energy. As viewed from earth, the sun subtends an angle of only 32 minutes (about the same as the moon).

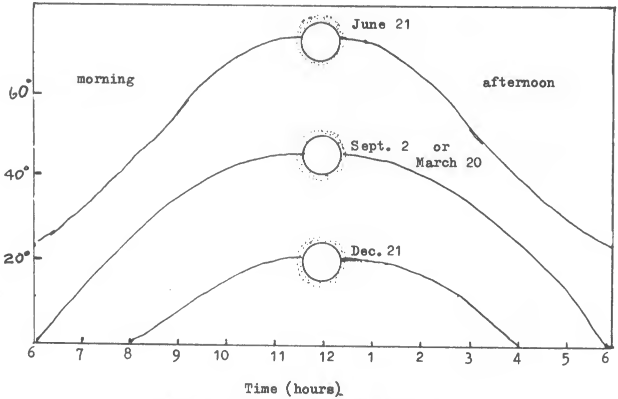
If we were to place our solar radiation measuring instrument on a satellite circling the earth above the atmosphere, the instrument would read about 1353 watts/square meter or 1.353 kW/m^2 when pointed directly at the sun. As this reading would not change more than a few percent throughout the year, it is called the "solar constant".



The Solar Constant

Sun-Earth Relationships

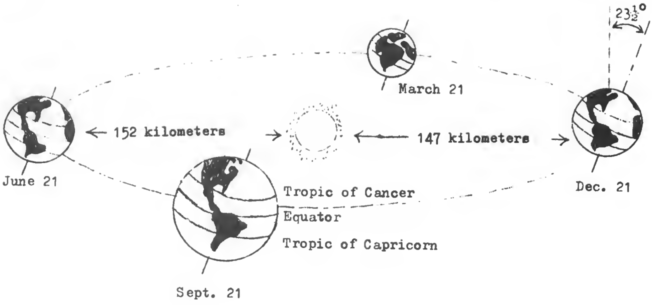
The sketch below shows the seasonal variation of solar altitude. It depicts the apparent "path" of the sun as viewed from Montana looking due south.



Apparent Path of Sun at 47°N Latitude
(June, September, and December)

To understand these seasonal differences we must study the geometrical relationships between the sun and the earth.

The picture following depicts the motion of the earth around the sun. Note that the picture is not drawn to scale; the size of the earth has been greatly magnified.



There are two features depicted in this sketch which have a bearing on the solar energy we receive on earth.

(1) Note that the orbit of the earth around the sun is not circular but is elliptical. This eccentricity amounts to about ± 1.7% variation in the distance between the sun and the earth. In the northern hemisphere we are closer to the sun in the winter than in the summer. Our solar radiation measuring instrument in the satellite would therefore read <u>higher</u> in the winter. Scientists have measured yearly variations in the solar constant of ± 3.5%.

Now you might ask, "If we are closer to the sun in the winter, why isn't January warmer than June?" To answer this question we have to look again at the sketch of the earth's orbit around the sun.

(2) Note that the earth is <u>tilted</u> (at about 23½°) with respect to the normal plane of the orbit. This tilt explains the fact that in the summer the sun appears higher or more nearly overhead in the northern hemisphere. In the winter the sun comes to our hemisphere at a lower angle, and hence appears closer to the horizon.

The sketches on the next page illustrate the angle of the sun's rays with respect to the apparent horizon in Montana. The first sketch illustrates the sun-earth relationship at noon on December 21, the winter solstice. Note that in the southern hemisphere on this day, the sun is directly above the Tropic of Capricorn. In other words, if you were on the Tropic of Capricorn the sun would be directly overhead, straight up, or 90° up from the apparent horizon.

In Montana on the same day at solar noon the sun would be at the angle above the horizon given by the equation

on Dec. 21, solar altitude $= 90^{\circ} - \phi - 23.5^{\circ}$

where ϕ is the local latitude.

For example, the latitude of Gardiner is about 45°. The altitude of the sun above the horizon, on December 21, in Gardiner is calculated by the equation as

$$\text{solar altitude} = 90^{\circ} - 45^{\circ} - 23.5^{\circ} = 21.5^{\circ}$$

The second sketch shows the position of the sun on June 21. Note that on this day the sun is directly above the Tropic of Cancer. At noon on this day the solar altitude can be calculated from the equation:

on June 21, solar altitude $= 90^{\circ} - \phi + 23.5^{\circ}$

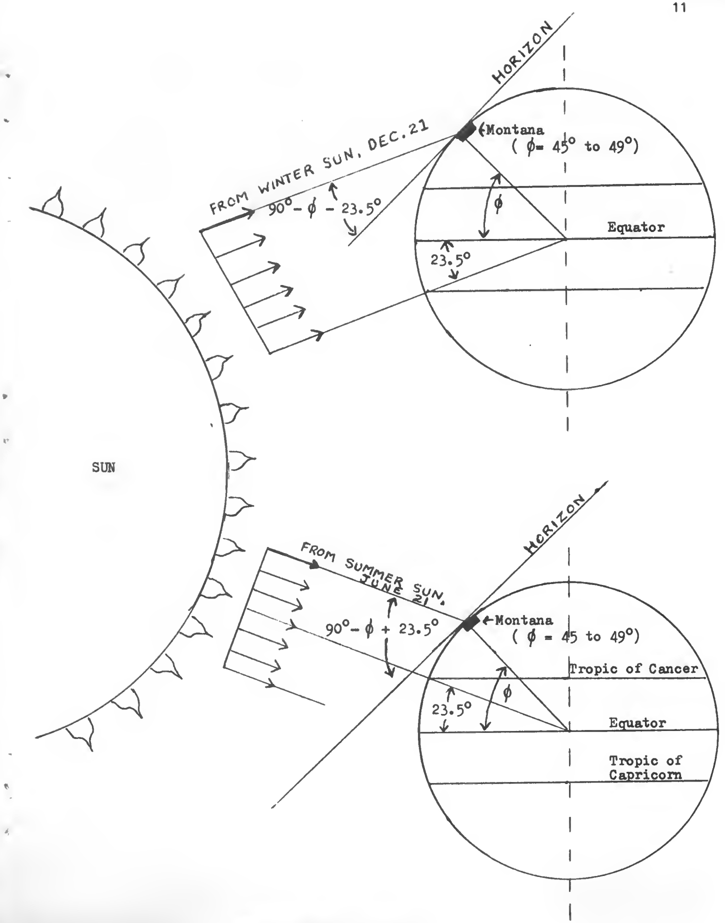
where ϕ is the latitude.

For example, Glasgow is at a latitude of approximately 48°. At solar noon on June 21 we calculate

$$\text{solar altitude} = 90^{\circ} - 48^{\circ} + 23.5^{\circ} = 65.5^{\circ}$$

thus the sun would appear 65.5° up from the horizon.

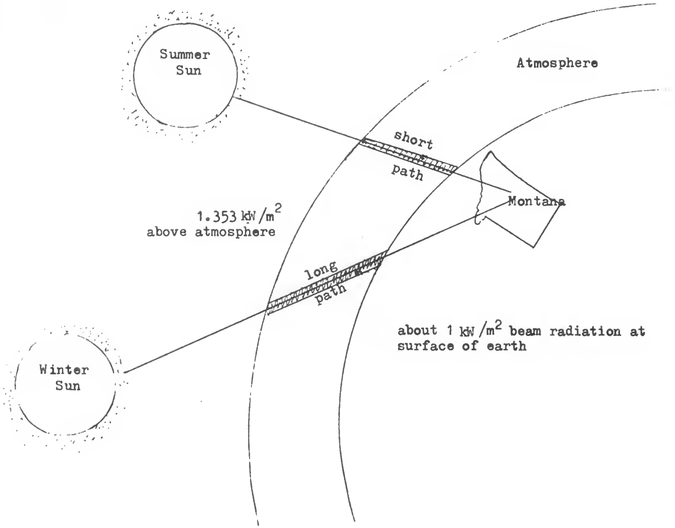
You can derive these equations for yourself using only the figures and geometry. Another good exercise is to calculate the solar altitudes for your location on June 21 and December 21.



Position of sun at noon

Atmospheric Absorption

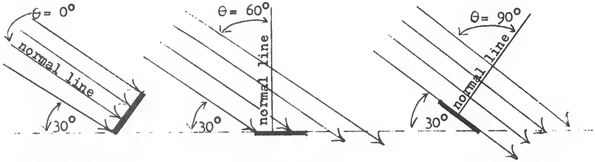
The atmosphere absorbs some of the solar radiation. This means that the radiation on the surface of the earth will be less than the solar constant. The amount of energy blocked by the atmesphere depends primarily on the amount of moisture in the atmosphere and the total path length through the atmosphere. In winter the path of the sun's radiation through the atmosphere is <u>longer</u> because of the sun's low angle. This is illustrated in the sketch below (which is not to scale).



The Cosine Law

To understand the explanation for "Why is it cold in the winter?" you have to understand the important effect on solar energy of angle to the sun.

In the sketch below we show a surface at three different angles to the sun. In the first part of the sketch the surface is directly perpendicular to the sun's rays. It is facing the sun directly; hence, the "angle to the sun" is 0^o. (A scientist might define "angle to the sun" as "the angle between the sun and a normal to the surface".) This "0^o" surface receives the maximum solar energy. Any motion of the surface will cause it to face away from the sun, and hence it will intercept less radiation and less energy. The second part of the sketch shows a plate facing 60^o away from the sun. You can see that half of the sun's rays pass on by the plate. The third part of the sketch shows the extreme example, where the surface faces 90^o away from the sun and all the radiation passes by.



collects 100% of energy
$\cos 0^o = 1$
1 kW/m^2

collects 50% of energy
$\cos 60^o = 0.5$
0.5 kW/m^2

collects 0% of energy
$\cos 90^o = 0$
0 kW/m^2

The relationship between the amount of solar radiation on the surface, the angle between the sun, and the direction of the surface can be written very easily using the cosine function. If θ is the angle to the sun, then

$$\begin{bmatrix}\text{Solar radiation on} \\ \text{surface at angle } \theta\end{bmatrix} = \begin{bmatrix}\text{Direct radiation} \\ \text{on normal surface}\end{bmatrix} \times \text{Cos } \theta$$

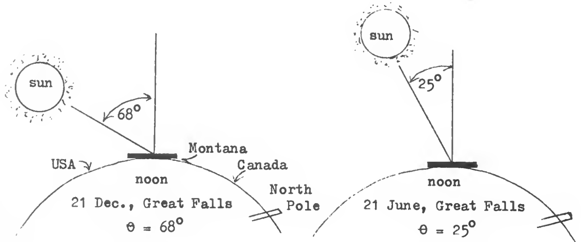
The use of the Cosine Law is illustrated in the sketch. If we assume the radiant energy per unit time on the normal or perpendicular surface is 1 kW/m^2, then we can use the Cosine Law to calculate the insolation on the other surfaces.

We should mention here that the "cosine law" is valid only for the direct beam radiation. On the surfaoe of the earth we receive direct beam radiation as well as diffuse radiation. The diffuse radiation comes to us due to reflections from our atmosphere. On an overcast or cloudy day 100% of the solar radiation reaching us is diffuse radiation.

On a clear day about 80% of the radiation is direct beam radiation and the remaining 20% is diffuse. Since most of the radiation is beam radiation, on a clear day the "cosine law" will give a fairly accurate description of the radiation on tilted surfaces. If you go through Experiment 2 you will understand more about using the "cosine law".

The Cosine Law: Summer and Winter

Now we can explain, in part, why it is cold in the winter in Montana, using the Cosine Law. First, the surface receiving radiation is the land itself, which faces approximately straight up. Next, assume that the solar radiation on a surface directly facing or normal to the sun is 1 kW/m^2, as in the previous example. The sketch below shows the angle to the sun in summer and winter and the energy falling on the land at noon.



$\theta = 68°$

$\cos\theta = 0.37$

$\text{Energy} = 1\ \frac{kW}{m^2} \times 0.37$

$= 0.37\ kW/m^2$

$\theta = 25°$

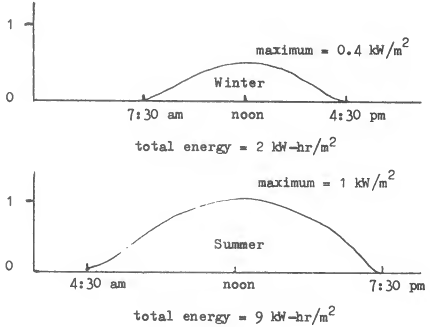
$\cos\theta = 0.91$

$\text{Energy} = 1\ \frac{kW}{m^2} \times 0.91$

$= 0.91\ kW/m^2$

This example shows that at noon in the summer the ground is receiving about <u>twice</u> the solar radiation as in the winter. The days are also much <u>longer</u> in the summer, which means that more total energy will be falling on the surface of Montana.

The following sketch depicts clear-day solar energy falling on a horizontal surface. (If your school is taking part in the solar energy measurement program, you will be familiar with this type of daily solar energy record.) These curves would be typical clear-day records of solar radiation in Great Falls, Montana.

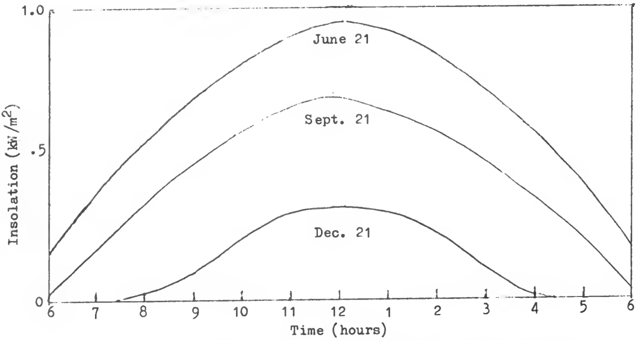


This graph puts together the two solar facts we have discussed in the preceding paragraphs:

1) The solar radiation fallimg on a horizontal surface in the summer is more intense throughout the day and lasts longer.
2) The solar radiation falling on a horizontal surface in the winter is less intense and occurs for a much shorter period.

The total solar energy available during any day is proportional to the area under the curve. We have calculated the total solar energy and shown the results in the figure. We can now see that the solar energy falling on the ground in the summer is 9 kw-hr on each square meter each day. This is over 4 times the 2 kW-hr/m^2 which falls on the ground in the winter. This large difference in solar energy is the predominant reason for the dafferences between summer and winter.

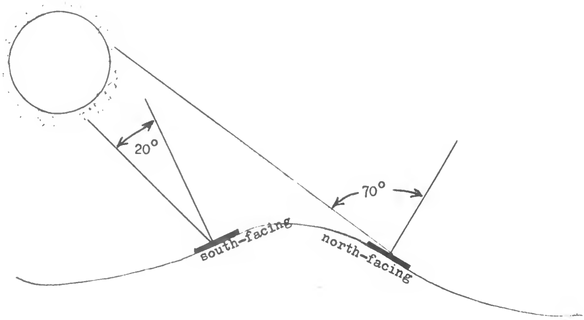
The sketch below shows insolation on a horizontal surface located at 48°N latitude on a clear day.



Insolation on a Horizontal Surface Located at 48°N Latitude on a Clear Day

Other Applications of the Cosine Law

A south-facing hillside intercepts much more solar energy than a north-facing slope. Study the sketch below.

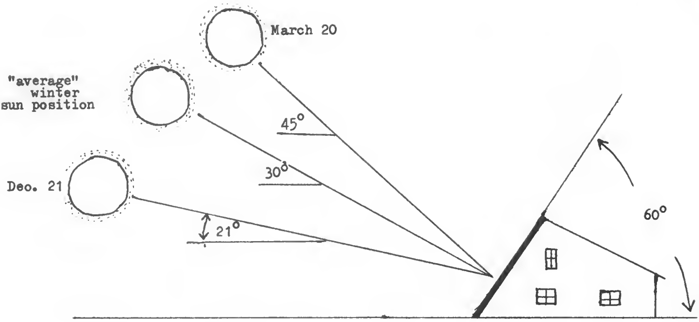


$$\text{Cos } 20^\circ = 0.94 \qquad\qquad \text{Cos } 70^\circ = 0.34$$

$$\text{ratio} = \frac{\text{south}}{\text{north}} = \frac{0.94}{0.34} = 2.8$$

The ratio of maximum radiations is about 2.8. It is clear that this large difference in solar radiation will have a large effect on the micro-climates of the south- and north-facing slopes. Consider where the snow melts first. Notice the vast differences in vegetation on south- and north-facing slopes. These phenomena are all related to the amounts of solar energy falling on the ground.

If you have seen solar-heated houses you probably noticed that the surface of the solar collector is tilted up at a steep angle. The sketch on the following page illustrates a side view of a collector on a house as well as the altitude of the sun at noon.



Note that during the winter season in Montana on the average the sun is about 30° above the horizon at noon. If we tilt a solar collector 60° above the horizon and face it due south then it will be perpendicular to the average winter sun. According to the "cosine law" the maximum radiation will be received on a surface that is perpendicular to the rays of the sun. From these considerations you you will understand why someone in Montana might tilt their collector at 60° to provide solar heat to their house in the winter.

Suppose you wanted to use a solar collector to heat a swimming pool during the summer or to dry grain during the fall. Can you calculate tilt angles for these collectors so that they will receive the maximum radiation? Suppose practical considerations dictated that your collector had to be tilted 10° away from the optimum angle. Can you use the cosine law to estimate the reduction in the solar radiation due to this 10° deviation? If you understand the sun-earth relationship and the cosine law presented in the past few pages, you will be able to solve a number of practical solar engineering problems.

Heat from the Sun

You have now seen some interesting things about the sun and the earth and how the radiation we receive from the sun depends on the season, angle, and absorption in the atmosphere. Now let's make a closer examination of what takes place when the sun shines on an object.

Suppose we set a rock in the sun—what happens? Well, if the rock is cold, it gradually heats up and becomes warm. If the sun keeps shining the rock will eventually reach a temperature warmer than the air around it and will reamin close to this temperature.

When the sun shines on the rock part of the sun's radiant energy is absorbed by the rock and part is reflected. The amount absorbed depends on the rock's color, how smooth its surface is, and the materials of which the rock is made. The ratio of the amount of energy absorbed to the amount of radiation striking the rock is called the rock's absorptivity.

$$\text{absorptivity} = \frac{\text{energy absorbed by body}}{\text{energy striking the body}}$$

If the rock is still cold the absorbed energy is stored by the rock which increases its temperature. As the rock becomes warmer it will eventually get hotter than the surrounding air, then part of the energy absorbed by the rock will be lost to the air around it. This is illustrated in the following figure. (Some energy might also be lost by conduction to the ground under the rock and the rock might also radiate some heat. To simplify our discussion, we'll assume little energy is lost to the ground or by re-radiation and just consider heat lost to air.) If the sun shines on the rock for a long enough time, the rock will reach a temperature high enough so that all the absorbed radiation is lost to the surrounding air, no more energy will be stored, and so the rock will remain at that temperature. The rock is now said to be in equilibrium.

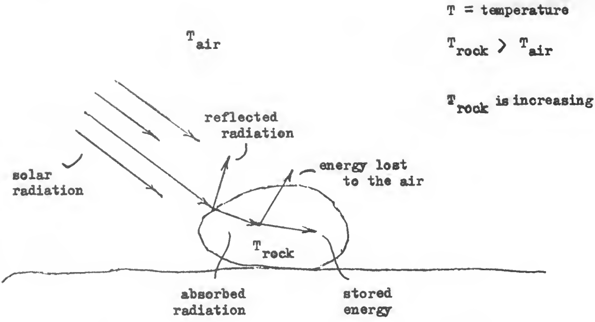


Figure 1: A rock being heated by the sun

The energy stored in the rock per unit time (in units of Joules/sec) can be related to its mass and change in temperature in the following manner:

$$\text{Energy stored per unit time} = \frac{mc_p \Delta T_{rock}}{\Delta t} \qquad (1)$$

where m is the rock's mass in kg, ΔT is the rock's change in temperature in $^{\circ}C$, Δt is the time in seconds it took for the rock's temperature to change, and c_p is the rock's specific heat with units of Joules/kg-$^{\circ}C$. (The Greek letter Δ, "delta", is commonly used in equations as an abbreviation meaning "change of".)

The energy being lost to the air is given by

$$\text{Energy being lost per unit time} = uA\,(T_{rock} - T_{air}) \qquad (2)$$

where u is the overall heat transfer coefficient with units of Joules/m^2-sec-$^{\circ}C$ for the rock and A is the surface area of the rock exposed to the air. The overall heat transfer

coefficient must be determined from experiments and practical experience with similar situations. This coefficient would be classified as an "empirical constant" by a scientist or engineer.

Combining the two we have,

$$\text{energy being absorbed per unit time} = \text{energy stored per unit time} + \text{energy being lost per unit time}$$

or

$$\text{energy being absorbed per unit time} = \frac{mc_p \Delta T_{rock}}{\Delta t} + uA\,(T_{rock} - T_{air}) \qquad (3)$$

Study this equation carefully. Notice that as the rock's temperature increases more energy is being stored in the rock and at the same time energy is being lost to the air at an increasing rate. Finally a temperature will be reached where the energy being absorbed is equal to the energy being lost and the rock remains at a fixed temperature ($\Delta T_{rock} = 0$). The rock is said to be in a state of "thermal equilibrium".

The above equation can be used to describe the energy gained or lost by any object. Using a house, for an example, suppose that the house stays at the same temperature ($\Delta T_{house} = 0$). The stored energy in the house does not change because the house temperature is fixed and equation (3) reduces to

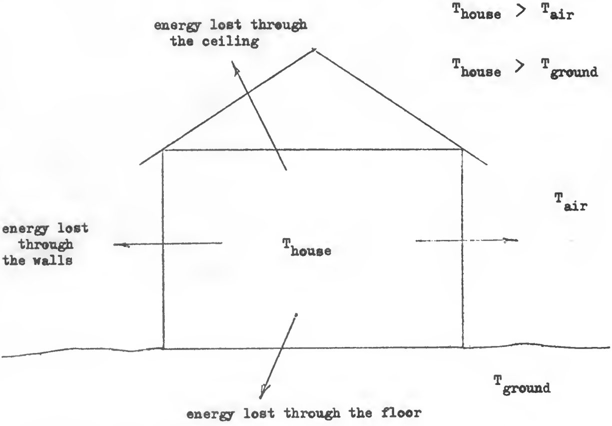
$$\text{energy being supplied per unit time} = \text{energy being lost per unit time} = u_{house} A_{house}\,(T_{house} - T_{surroundings})$$

This energy loss can be further divided into the energy lost through the walls, the ceiling, and the floor as shown in the following figure.

This figure presents a simplified breakdown of the energy losses in a house along with an equation representing this breakdown. Engineers use equations like this to predict the heat loss of new buildings. These calculations allow them to select the size of solar heating systems and/or

furnace to place in the building. Some of the books listed in the References give these procedures in greater detail.

You can see that as the difference between the house temperature and the surrounding temperatures (i.e., air temperature, ground temperature) increases, more energy is lost and so more must be supplied to the house from a heater. Also if the value of u is made smaller, less energy will be lost by the house.



$$\text{Energy being lost per unit time} = u_{walls} A_{walls} (T_{house} - T_{air}) + u_{ceiling} A_{ceiling} (T_{house} - T_{air}) + u_{floor} A_{floor} (T_{house} - T_{ground})$$

The value of u depends primarily on the amount of insulation.*
The more insulation the smaller the value of u. A common term used to give the insulating value of a wall, a floor, a ceiling, or insulation is the "R" value. The R value is simply the reciprocal of u, that is,

$$R = \frac{1}{u} \qquad (5)$$

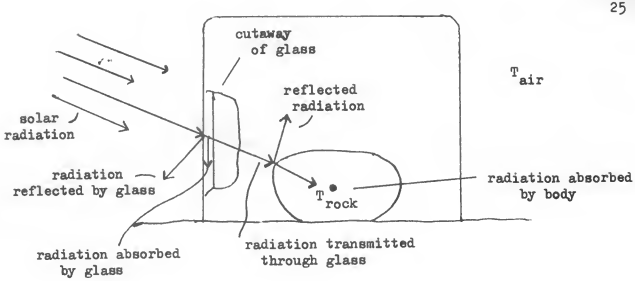
The units of R are commonly expressed as hr-ft^2- $^\circ$F/Btu.

So, when you hear a house has R-12 walls or an R-30 ceiling you will know that this simply tells how well the house is insulated, and the bigger the R value the better the insulation.

Let's return now to the rock and investigate something new. Suppose the rock has been setting in the sun for awhile a has come to equilibrium. We now set a clear glass jar over the top of the rock. What will happen? In general, the rock's temperature will increase due to what is called the "greenhouse effect". The rock will also reach a higher equilibrium temperature.

When the sun strikes the glass jar, part of the radiation is reflected by the glass and part is absorbed by the glass, but most of the radiation will be transmitted by the glass. This is shown in the following figure. (A single layer of glass will transmit about 80% of the radiation striking it.) The transmitted radiation will strike the rock as before. But why then does the rock's equilibrium temperature increase if it is receiving slightly less radiation than before? The answer is that there is a larger decrease in the energy lost.

* Notice the similar spellings of ins<u>u</u>lation and ins<u>o</u>lation. Insulation refers to the resistance to heat flow. For example, "My house has 20 cm of fiberglass insulation in the attic; it is well insulated". Insolation refers to solar radiation: the rate of radient heat flow from the sun. For example, "Yesterday at noon I measured the solar insolation with the SIMM manual meter. The solar insolation was 1 kW/m^2."



A rock being heated by the sun under a glass jar

Glass, although transparent to visible light, blocks thermal radiation. This type of radiation is called infrared and is what you feel when you stand by a fire or heater. The thermal radiation given off by the rock is reflected by the jar as depicted below.

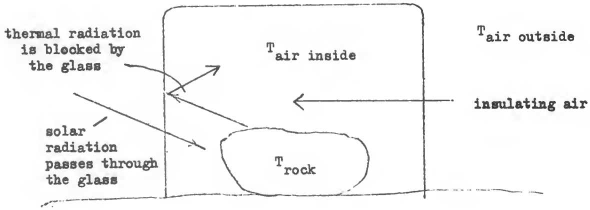


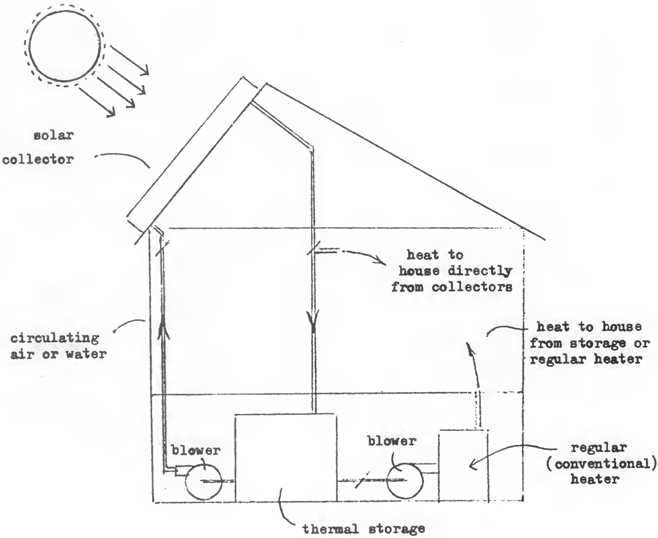
Figure 4 : A rock under a glass jar in the sun

Also the air inside the jar acts to insulate the rock from the outside air. The air inside is warmer than the air outside. Both of these effects give rise to a "greenhouse effect". The combined effect can be thought of as a decrease in the value of u, the overall heat loss factor, in equation 3. Although the energy per unit time absorbed has decreased due to the slight decrease in the solar radiation, the even greater decrease in the energy per unit time lost (due to the reduction in u) causes the rock to have a higher equilibrium temperature.

Applications of Solar Energy

The energy of the sun can be used for many special and varied purposes. One of its most common and practical applications is the heating of a home.

The basic components of a solar heating system are shown below.



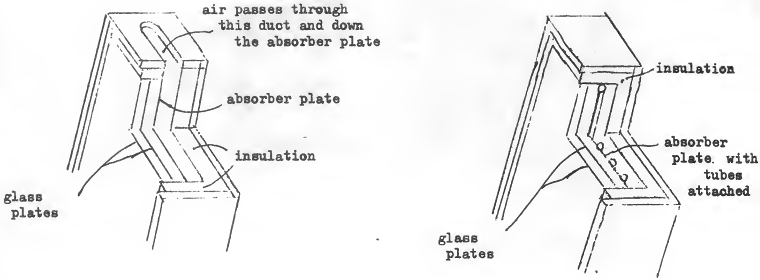
Components of a solar heating system

The collectors absorb the solar radiation which is then used to heat the house or heat the storage. The reason for the thermal storage is that you cannot turn the sun on and off at will. When the sun is out, the collectors absorb all the energy they can; if more energy is collected than is needed to heat the house, it is transferred to the storage. This excess energy in the storage can then be used to heat the house when the sun is not available, like at night or on a cloudy day. An auxiliary heater must also be installed in the house along with the solar heating system for those times when the sun is obscured by clouds for several days or when outside temperatures are very low.

Either water or air is commonly used to circulate through the collector to pick up heat and deliver it to the storage. If air is used, the air which is blown through the collectors can be blown directly into the house for heating. If water is used, a heat transfer device such as a radiator or baseboard unit is usually employed to transfer heat from the circulated water to the air to heat the house.

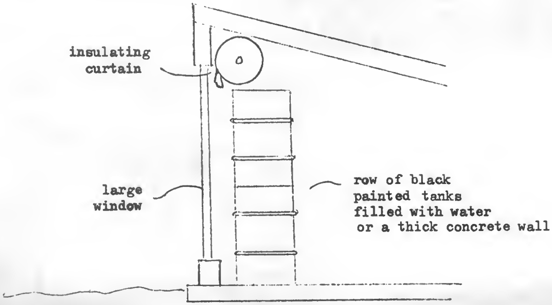
The storage unit is usually composed of a large insulated box of rocks for an air system. Air from the collectors is blown through the rocks to heat them. Air from the house can then be blown through the rocks when heat from the storage is desired. For a water system a large tank filled with water is usually used for storage.

An illustration of the typical construction of an air and a water collector is shown in the following figure. The absorber plate is coated with black paint or a special coating so that it absorbs nearly all the solar radiation falling on it. Air or water is then circulated past the absorber plate to pick up the heat. Glass plates (usually two for our cold climate) are placed in front of the absorber plate to take advantage of the greenhouse effect from the glass and to cut the heat loss from the absorber plate. Insulation is also placed around the sides and on the back of the collector to reduce heat loss.

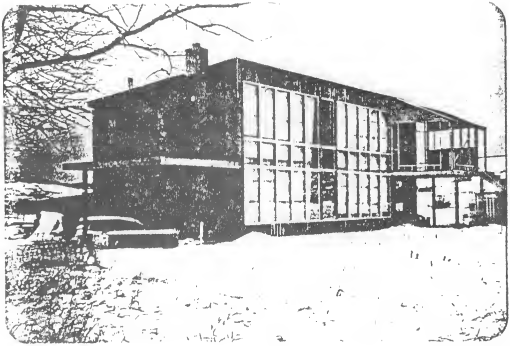


An air and water solar collector

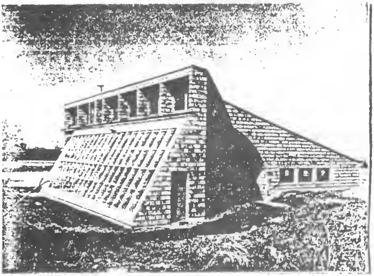
Up to now we have only been discussing active solar heating systems. An active solar heating system is one in which the collectors and storage are separate pieces and a circulating fluid, usually water or air, is used to transfer heat from the collectors to the storage. A system in which the collectors and storage are combined in one piece is called a passive solar heating system. Such a system is illustrated below.



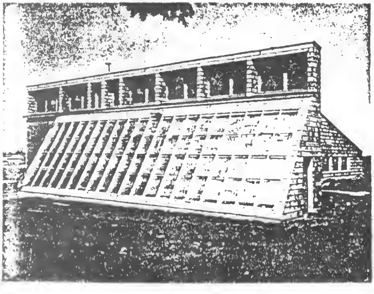
A passive solar heating system



Passive solar home



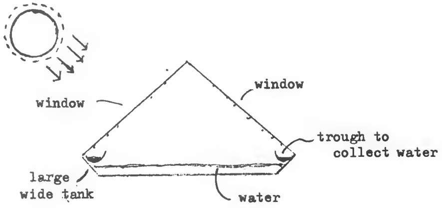
Two views
of an
active
solar home



In this system the tanks or concrete forming the solar wall act as both the collectors and the storage. Water in the tanks is heated during the day as the sun shines through the window. This stored heat is then used to heat the house at night or on a cloudy day. In cold climates such as Montana a large insulating curtain is lowered between the solar wall and the windows when the sun is not shining to reduce the heat lost through the window. The preceding page shows pictures of an active and a passive solar house located in Bozeman.

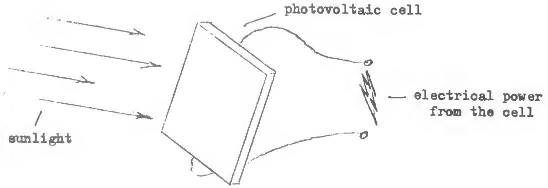
The sun's energy may also be put to the useful application of distilling water. This would be very beneficial in areas where fresh water is scarce but salt or brackish water is available. However, although the process is simple and technologically feasible, and although the sun's energy is free, the cost to produce solar-distilled water on a large scale is very high and not always economically feasible. This is due to the large investment in materials which must be made to construct a large solar distiller.

To illustrate the simplicity of the solar distiller, all that is needed is a large open container to hold the water which is evaporated when heated by the sun and a window to condense and collect the evaporated moisture as shown below.



A solar distiller

Using a device called a photovoltaic cell the sun's radiation can be converted directly into electricity. Sunlight striking the cell is converted to a flow of electrons and electricity can be transmitted along the 2 wires leading out of the cell. The figure below illustrates this process.



A photovoltaic cell

The high cost to produce the cells makes it impractical to use this device to produce electric power on a large scale at the present time. Its present applications are limited to special projects like the space program and satellites where photovoltaic cells are used to power instruments in the craft, and also to novelty items such as solar powered transistor radios and watches.

We have just covered some of the current applications of solar energy. Although the sun has been with us for millions of years, the technology making direct use of solar energy is still in its infancy. Many more useful and marvelous developments are yet to come. We are just beginning to learn how to make practical use of our sun.

Introduction to Experiments

In the previous sections we have covered some of the basic facts and mechanisms relating to the sun and the sun's relationship to the eatth. We have discussed the measurement and utilization of solar energy as well as how solar energy arrives on the surface of the earth and how all this relates to our major seasonal weather cycles. You may feel that we have covered a lot of facts, equations, and pictures in these past few pages; rest assured that this is just a brief overview of our knowledge and beliefs about the workings of the sun, its influence on the earth and the weather, etc. You are encouraged to pursue these studies further. A bibliography is included which lists books that should be hlepful in expanding your knowledge of solar science and teohhology.

The remainder of this book consists of experiments which I hope will be interesting to you and have educational value. As you do the experiments refer back to the text and read it again. By going back and forth between experiments and text you will find that you will learn a great deal about solar energy.

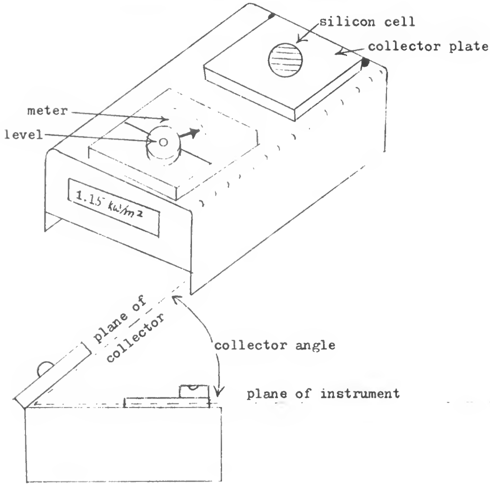
The materials for most of these experiments should be available at your school. The SIMM manual solar energy meter is an important part of most of these experiments and the first experiment is intended to familiarize you with this device.

The solar collector experiments require some construction effort on your part. I have tried to design the test collectors so that you will be able to get the materials for them locally and build them as a class project. If you have a school shop, the shop teacher can probably help you with the construction.

Most of the experiments have several parts and variations. You are encouraged to at least try carrying out the initial parts of the experiment. For example, I would suggest that you build the solar collectors and at least look at them in operation. More interested or advanced students should take the next step and make specific measurements and calculations to find the actual efficiency of the device.

The advanced parts of these experiments will take you past the "Gee whiz, ain't it hot" level of understanding. These experiments require your time, patience and attention. Although the apparatus may be simple and your measurements approximate the experiments are not just "kid stuff". You will find that engineers, scientists, and technicians working in the field of solar energy utilization use the same basic concepts and methods you will be using. Their equipment is more elaborate and their measurements are more precise, but the basic principles are much the same. If you can work through all the experiments and understand them you will know a lot of the basics of solar utilization.

SIMM Manual Solar Energy Meter



Construction. The SIMM manual instrument consists of a silicon cell, mounted on a hinged plate, and a read-out meter. Solar radiation striking the silicon cell produces an electrical output which is indicated on the meter. The circuit includes a shunt resistor which allows the meter to be calibrated to measure the solar flux or insolation.

The hinged plate can be oriented at various angles for experimental purposes. When the plate is folded against the case, the bubble level

can be used to level the plate. Pick up the instrument and familiarize yourself with it.

Operation. The meter indicates the solar radiation falling on the hinged plate. Each instrument has a "calibration factor", which is printed on the case. This calibration factor is the solar power in kilowatts per square meter (kW/m^2) which will cause the meter to deflect full scale (a reading of 1). To convert the meter reading into solar power you must multiply it by the calibration factor.

$$\boxed{\text{Solar insolation} = \text{Calibration factor} \times \text{Meter reading}}$$

For example, assume your instrument has a calibration factor of "1.15 kW/m^2 FS" (meaning 1.15 kilowatts per square meter—full scale). Assume the sun is falling on the instrument and the meter reads 0.82. The solar radiation falling on the instrument is simply 1.15 kW/m^2 x 0.82 or 0.94 kW/m^2 (kilowatts/square meter). Written in the format of the previous equation:

$$\begin{aligned}\text{Solar insolation} &= 1.15\ kW/m^2 \times 0.82\\ &= 0.94\ kW/m^2\end{aligned}$$

Care and Maintenance. The manual instrument is fairly durable but should be handled like a watch or a radio. Don't drop the instrument; don't leave it in the rain; don't poke and pry around on the wires or the silicon cell.

The silicon cell should be gently wiped if it gets very dirty. Small amounts of dust or dirt are unimportant. The zero on the meter can be adjusted by removing the plastic cover.

NOTE: A STATIC ELECTRICAL CHARGE ON THE PLASTIC METER COVER MAY CAUSE ERRATIC AND ERRONEOUS READINGS. To remove the charge, simply "breathe" on the meter. The moisture in your breath will help dissipate the charge.

Experiment 1: Using the SIMM Manual Solar Energy Instrument

The purpose of this first experiment is to familiarize you with the operation of the SIMM solar energy instrument. Pick a fairly clear day to do this experiment. Remember: THE METER READING IS ALWAYS PROPORTIONAL TO THE SOLAR RADIATION STRIKING THE COLLECTOR PLATE.

Converting a meter reading to solar insolation. The basic equation you will use is:

Solar insolation = Calibration factor x Meter reading

The calibration factor will be printed on your instrument and will read something like this:

$1.07\ kW/m^2$ FS

This means

1.07 kilowatts per square meter, full scale

(The actual number on your instrument is probably not 1.07, as each instrument is calibrated individually.) Thus, if the solar flux falling on the collector plate is $1.07\ kW/m^2$ the meter will read "1", which is the full scale deflection of the meter. The meter reading is a number between 0 and 1. Look at the meter face and see if you can figure out the markings.

Using the meter to measure solar radiation. Take the instrument outside and place it on the ground. Fold the collector plate flat against the meter case. Level the instrument using the bubble level on the case. Take a meter reading. Now multiply this reading by the calibration factor to find the solar radiation. This is the radiation striking the ground. (How might this reading change with the seasons?)

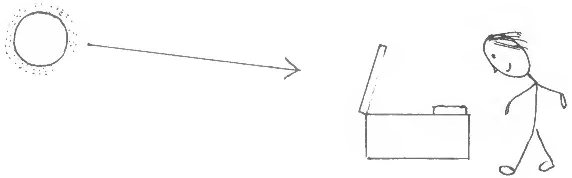
Raise the collector plate and point it directly at the sun. What is the maximum meter reading you can observe? Calculate the solar insolation (solar radiation).

Level the meter; then raise the collector plate to give the largest meter reading. Now take a protractor and figure out how to measure the angle between the collector plate and the top surface of the instrument. What is the angle?

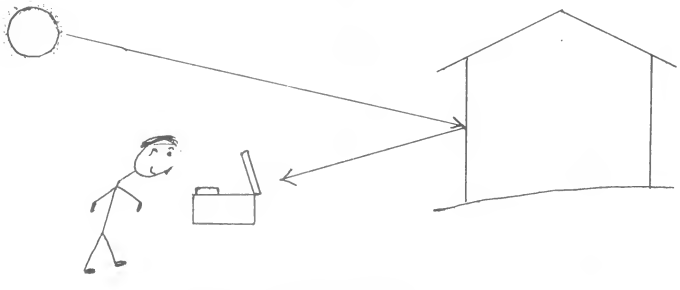
Transmission and Reflection. Measure the solar radiation transmitted through a glass window on your school building. Compare the reading

in front of the glass to the reading behind the glass. How much solar power is lost? Is the window clean? How much difference is there between a clean and a dirty window?

Measure the solar radiation reflected from a sunlit wall by aiming the SIMM meter at the wall. Look around at other sunlit objects and surfaces. How much radiation is reflected from a tree or the grass? How much is reflected from the parking lot? How much radiation is reflected from a window? Measure reflections from a mirror or a snowbank.



measuring direct beam radiation



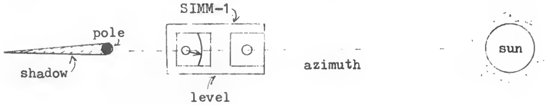
measuring reflected radiation

Experiment 2: Collector Angles—The Cosine Law.

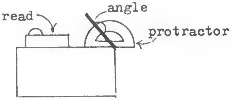
The best time to do this experiment is on a clear day between about 10 a.m. and 2 p.m. You will need 10 or 20 minutes without clouds to do this experiment.

Take the SIMM-1 outside to a clear, sunny location. Determine the azimuth (bearing or direction) of the sun. The shadow of a vertical telephone pole, flag pole, or meter stick will help you determine the direction. You can probably estimate it by eye.

Set the SIMM-1 on the ground and line it up with the azimuth of the sun. Adjust it for level.



Starting with the collector plate in the horizontal position, take a reading of the meter. Raise the hinged collector plate 10° (using a protractor) and take another reading.

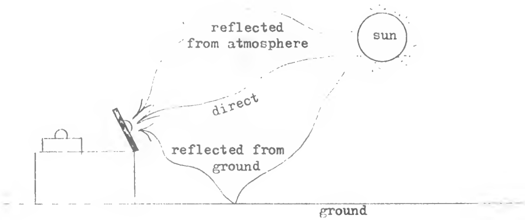


Continue these readings every 10° up to 90°. Record these readings in a table (such as the one shown at the end of this experiment).

Exercises.

1. Multiply these readings by the calibration factor to obtain solar radiations and enter these values in the table.
2. Using graph paper, plot the solar insolation versus angle. The table and graph I made when I did this experiment in Bozeman can be used as a sample form. They are at the end of this experiment.
3. The graph will probably have a maximum energy value. Locate this value and determine the angle at which it occurred. The maximum occurred when the collector plate was directly facing the sun.
4. Add a "deviation angle" column to the table. The deviation angle is the difference between the angle in the table and the angle of maximum radiation. The deviation angle measures how many degrees the collector was facing away from the sun. In the next column enter the cosine of the deviation angle. (Use trig tables or a calculator.)
5. In the next column multiply each cosine by the maximum radiation at zero deviation.
6. These are calculated radiations based on the Cosine Law discussed in the Introduction. Compare these calculated values to the actual measured values.

Reflections. The collector receives direct radiation from the sun plus reflected radiation from the atmosphere and from the ground.



These reflections will cause the radiation received from the collector to depart from a simple Cosine Law. The reflections from the ground are quite large when it is covered with snow and the sun is at a low altitude. These reflections will most affect the readings when the collector angle is near 90°. Specific consideration of these reflections leads to variations of this experiment:

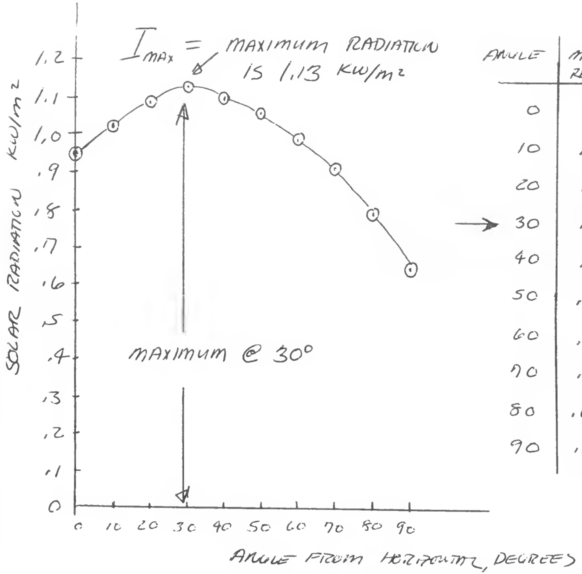
1. "Winter Experiment". Pick a clear day with snow cover for the experiment.
2. "Summer Experiment". Pick a day with no snow cover for the experiment.

Simulations of the winter and summer experiments. The meter responds primarily to reflections from the ground surface directly in front of it. Thus, in the winter you can usually find a parking lot that is free of snow and can run the "summer experiment".

Similarly, you can run a simulated version of the "winter experiment" when there is no snow on the ground. Set the meter on the ground and lay out white paper on the ground directly in front of it (about 1 to 3 square meters of butcher paper will do). The paper will simulate snow by reflecting solar radiation into the instrument.

Reflection experiments. Follow the procedure outlined in the main experiment. Pay particular attention to the readings with the collector angle at 80° to 90° from the horizontal. December, January, or February will yield the largest reflections due to the low sun angle.

Data by C. Faulkes
Bozeman, MT
12 May 1977



MEASURED

PREDICTED USING COSINE LAW

ANGLE	METER READING	SOLAR RADIATION kW/m²	θ DEVIATION ANGLE FROM 30°	COS θ	$I_{max} \times \cos\theta$
0	.83	.95	30	.87	1.00
10	.90	1.03	20	.94	1.08
20	.95	1.09	10	.98	1.11
30	.98	1.13	0	1	1.13
40	.96	1.10	10	.98	1.11
50	.92	1.06	20	.94	1.08
60	.85	.98	30	.87	1.00
70	.79	.91	40	.77	.88
80	.68	.78	50	.64	.74
90	.56	.64	60	.5	.58

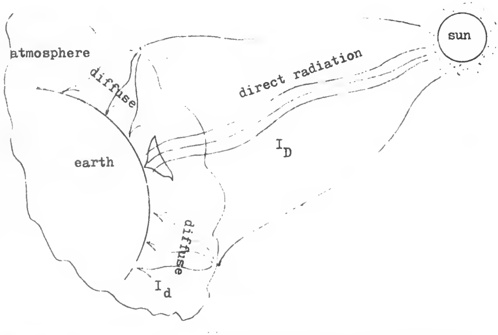
COMPARE

Experiment 3: Direct and Diffuse Radiation

The purpose of this experiment is to introduce the ideas of direct solar radiation and diffuse solar radiation, to measure direct and diffuse radiation on several days, and to correlate this with observations of the weather.

The total solar radiation falling on some point on the earth's surface is made up of direct radiation and diffuse radiation. The direct radiation is simply the "line of sight" direct radiation coming from the sun on a clear day. It is also sometimes referred to as "beam radiation".

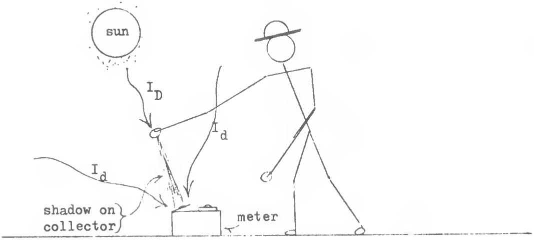
The diffuse radiation is a secondary or scattered radiation coming from the atmosphere or clouds. Particles of water, as well as solids, will scatter the direct solar radiation and this will reach the ground as diffuse radiation. You have probably been outside on lightly overcast days and felt diffuse radiation even though there was not enough direct radiation to cast a shadow. The sketch below depicts diffuse and direct radiation.



Experiment. The meter normally responds to the sun of the direct beam radiation (I_D) and the diffuse radiation (I_d). The meter reading is thus $I_D + I_d$.

We can approximately measure the diffuse radiation I_d if we block the direct radiation to the meter. This can be done by shading the collector plate of the meter. An easy way to shade the meter is with your hand. Note that you should hold your hand as far as possible from the meter. If you hold your hand too close to the meter you will block out diffuse radiation as well as direct radiation.

The sketch below illustrates one way to shade the meter.



Taking a reading of diffuse solar radiation, I_d, by shading the meter from the direct beam radiation, I_D

The data can be organized in the following way:

<u>measured data</u>

date - [illegible]

time - [illegible]

collector orientation - [illegible]

A	B
meter reading (unshaded)	meter reading (shaded)
[illegible].75	[illegible]

atmospheric condition - [illegible]

calibration factor - [illegible] kW [illegible]^2

calculated data

C	D	E		
A x 1.07	B x 1.07	C − D	$\frac{D}{C}$ x 100	$\frac{E}{C}$ x 100
Total Radiation (kW/m^2)	Diffuse Radiation (kW/m^2)	Direct Radiation (kW/m^2)	% Diffuse	% Direct
$I_D + I_d$	I_d	I_D		
1.02	0.56	.16	54	16

Experimental variables. Once you have mastered the techniques of measuring and calculating diffuse and direct components of solar radiation, you can do some extended experiments. These experiments require that several sets of measurements be made. Each set of data is handled just like the example just shown.

Variation 1.

(1) This experiment involves taking a set of readings at the same time each day for a week.

(2) The meter and collector plate are in the horizontal position.

(3) Record the shaded and unshaded meter readings and describe thoroughly the condition of the atmosphere (clear, type of clouds, haze, fog, etc.).

(4) Calculate % diffuse and % direct radiation for each day.

(5) Compare your measurements to your observations of the weather and try to reach some conclusions or generalizations.

(6) Think and read about plants and their requirements for direct and/or diffuse light.

(7) Extend your experiment to cover several weeks or months of data.

Variation 2.

(1) This experiment follows the same theme as the first variation. The collector is horizontal and the same observations and calculations are made.

(2) The readings in this variation are all made during the same day. Try to get at least six readings, one each hour or each class period throughout the day. It will be especially interesting if you can get some

readings near sunrise or sunset.

(3) Look at the data for % diffuse and % direct radiation. Compare these percentages with the atmospheric conditions existing when the readings were made.

(4) Compare these percentages with the angle to the sun. Compare morning and evening values with mid-day values.

Variation 3.

(1) In the first two variations the collector plate was horizontal. These results have some bearing on the solar energy striking the ground and hence the vegetation patterns, the distribution of snow, ground moisture, etc.

(2) In this experiment the collector plate is tilted 60^{o} up from the horizontal and faces due south (that's true south and not magnetic south). These results have bearing on solar collectors of the type used in solar-heated houses. (The 60^{o} tilt is chosen because it will be pointed nearly normal to the sun, on the average, during the winter months.)

(3) Readings of direct and diffuse radiation should be made throughout the day, at fixed intervals, along with observations of the atmospheric conditions.

(4) Calculate the percentage diffuse and direct radiation and correlate these with the atmospherio conditions and the angle to the sun.

(5) Assume that each reading was typical of the time interval. Multiply each radiation intensity by the length of the interval in hours. This gives energy in $kW\text{-}hrs/m^2$. Add together the direct energy. Add together the diffuse energy. How do they compare?

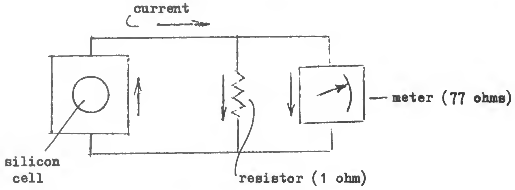
(6) A flat-plate solar collector will absorb both direct and diffuse radiation (just like the SIMM solar radiation meter). Concentrating collectors (parabolic reflectors, etc.) will collect only the direct or beam radiation. Think about this fact in relationship to your data on direct and diffuse radiation. We will build and test these two collectors in later experiments.

Experiment 4: Electricity Directly From the Sun

Electricity can be made directly from the sun using photovoltaic cells. Such a cell, a silicon cell, is the sensing device on the SIMM-1 instrument.

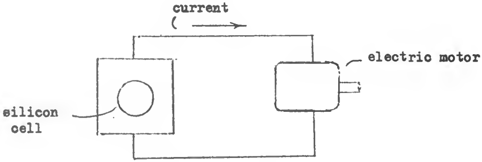
Materials: SIMM-1, calculator

The basic circuit of the SIMM-1 is shown below.



SIMM-1 circuit

When the cell is placed in the sun, current (electricity) flows through the silicon cell, through the meter and through the resistor. An alternate way to hook up a silicon cell might be the following. (WARNING: DO NOT TRY TO CONNECT YOUR SILICON CELL IN THIS MANNER, although you can find such devices in hobby stores.)

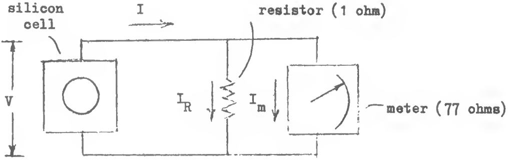


With this circuit, current from the silicon cell would be used to run the motor. You can calculate how much power is being generated by your silicon cell using the SIMM-1 and the following equation (derivation of which follows):

$$\text{power in milliwatts (1 milliwatt} = 1/100 \text{ watt)} = 6\ (\text{meter reading})^2$$

Take your SIMM-1 outside and make several readings. Try to get at least one maximum reading with the silicon cell facing directly at the sun. Now calculate the power the silicon cell is generating. How many silicon cells would it take to light 1-100 watt light bulb?

Derivation of Power Equation



SIMM-1 circuit

The power the silicon cell is generating can be found by

$P = VI$ where P— power (watts) (1)

V - voltage across the silicon cell (volts)

I - current through the silicon cell (amps)

or if V is in millivolts and I is in milliamps then

$P = \frac{VI}{1000}$ where P is in milliwatts (2)

The current through the silicon cell is

$$I = I_m + I_R \tag{3}$$

and the voltage across the silicon cell, the resistor and the meter are all equal to

$$V = I_R R_R = I_m R_m \tag{4}$$

where I - current through the silicon cell

I_R - current through the resistor

I_m - current through the meter

R_R - resistance of the resistor

R_m - resistance of the meter

Now equation 4 can be rearranged to solve for I_R as $I_R = I_m \frac{R_m}{R_R}$

and this can be substituted into equation 3 giving

$$I = I_m + I_m \frac{R_m}{R_R} = I_m \left[1 + \frac{R_m}{R_R} \right]$$

Substituting in the values of R_m and R_R we have

$$I = I_m \left[1 + \frac{77}{1} \right] = I_m 78 \tag{5}$$

Now substituting in values for equation 4 for the resistance of the meter

$$V = I_m 77 \tag{6}$$

Finally, substituting equations 5 and 6 into equation 2 we arrive at the power in milliwatts, P, where

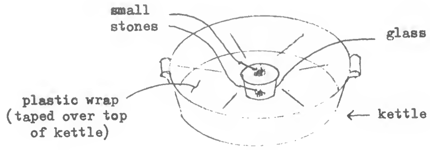
$$P = \frac{(I_m 77)\,(I_m 78)}{1000} = I_m^2\, 6 = (\text{meter reading})^2\, 6$$

Experiment 5: A Solar Water Distiller

The sun can be used to distill water with the simple appartus shown below.

Materials

- large kettle, approximately 4-7 liters
- clear plastic wrap to cover the top of the kettle
- small glass, approximately 100 ml.
- cellophane tape
- 2 small stones, about 2 cm in diameter (washed)
- about 1 liter of muddy water



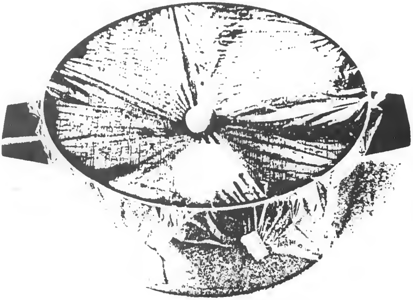
Solar distiller

First fill the kettle to about 2 to 4 cm with the muddy water, then set the empty glass in the middle of the kettle with the small stone inside so that the glass does not float. Tape the plastic wrap over the top of the kettle, leaving enough slack in the plastic so that when the second small stone is set in the middle of the plastic, directly over the glass, the plastic slopes gently down toward the glass. Be careful that the plastic does not touch the glass. The figure above and the photograph on page E15 illustrate the experimental set-up.

Set your solar distiller out in the sun for a few hours and see how much fresh water you can distill. You can check the purity of your distilled water by placing a few drops of the distilled water next to a few drops of muddy water on a piece of white paper and setting it out in

the sun. After the distilled and muddy water have evaporated how much residue is left from the distilled water, how much from the muddy water? How pure is your distilled water?

You can also distill clean water from salt water. Clean the apparatus and run this experiment again, substituting clear salt water for the muddy water (a couple of cc of salt in a liter of fresh water works fine). Set the distiller out in the sun for the same period of time as before. (Try to pick approximately the same time of day and also a day which is about the same temperature and which has about the same amount of sunshine as before.) Now how much fresh water did you distill? Was it more or less than the previous experiment? Why would there be a difference? You can check the purity of this distilled water by tasting it.



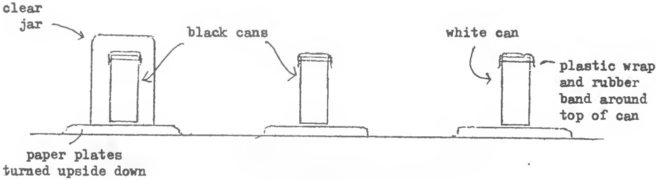
A simple solar distiller

Experiment 6: Passive Solar Collectors

The effect of absorptivity and a glass covering on the amount of energy an object absorbs from the sun can be illustrated by the simple set-up shown below. A photograph of our test apparatus is also shown on page E-17.

Materials

- 3 cans, of the same size (aluminum pop or beer cans work well)
- large clear wide-mouth jar (large enough to fit over a can)
- 3 paper plates
- flat black paint
- white gloss paint
- plastic wrap (about .1 m^2)
- 3 rubber bands
- thermometer (approximately 1-70° C)
- some water

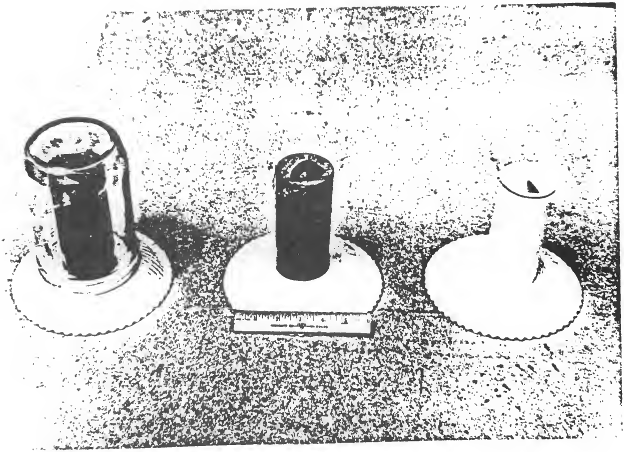


Experimental Set-up

Select a clear sunny day to run the experiment. Paint two of the cans black, one white and fill all three cans full to the same level with water. The water in all three cans should be close to the same temperature, within about a few ° C. Now place a small piece of plastic wrap over the top of each can and secure with a rubber band. This is to prevent evaporation of the water. Set the three cans in the sun on top of the inverted paper plates, with the large glass jar placed over one of the black-painted cans. The paper plates provide some insulation for

the bottoms of the cans. After the cans have been in the sun for a few hours measure their temperature. Which one has absorbed the most energy? Which is second and which is last? Can you explain the differences in temperature? Which can was the best collector of solar energy?

Is the solar heated water hot enough for a bath or to wash dishes? How big would the can have to be to heat enough water for a bath or a shower for your family? How long do you think it would take to heat your bath water? What color would you use for your solar water heater? How might you build it? Would it work in the winter?



Passive collector experiment

Experiment 7: Calculating Absorptivity of Different Colors

With this experiment you will be able to calculate the absorptivities of the black and white cans used in Experiment 6.

Materials

- 1 black and 1 white can used in Experiment 6
- 2 paper plates
- SIMM-1 solar radiation meter
- 2 thermometers (0–50°C or close to this range)
- a sheet of white paper (about 20 x 30 cm)
- a calculator
- ruler
- measuring cup, graduated cylinder or weighing scale

Select a clear warm day to run this experiment, between 10 am and 2 pm. About 2 hours are required to run the experiment. A diagram and photograph of the required set-up follow on the next page.

Make a small hole in the plastic on top of the cans so that a thermometer may be inserted to measure temperature. Both cans should be nearly filled with water to the same level. Also, the temperatures of the cans should be the same to within 1° C and within 3° C of the surrounding air. One easy way to accomplish this is to fill the cans with water before the experiment is run and let them sit in the shade.

Start the experiment by setting the two cans on the inverted paper plates in the sun. Record their temperatures, the air temperature and the time. Temperatures should be measured within .5° C and the time to the nearest minute.

We also need to know how much solar radiation or power is striking the cans. This is done by measuring the solar insolation on a horizontal surface and then measuring the surfaoe area of the can's shadow. Set the SIMM-1 on the sunlit table and measure the solar insolation with the

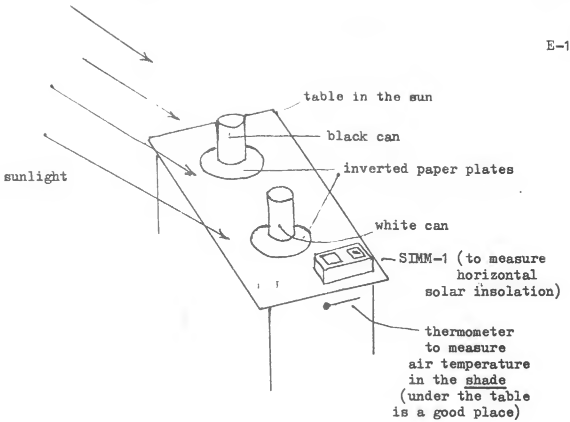
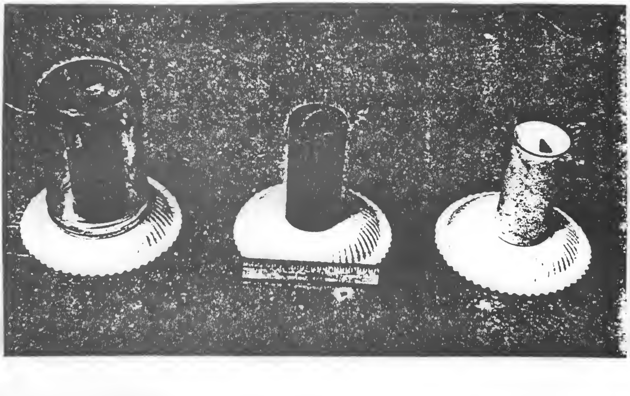
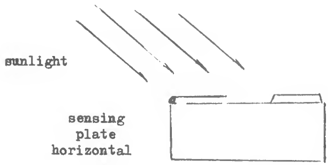


table in the sun
black can
inverted paper plates
sunlight
white can
SIMM-1 (to measure horizontal solar insolation)
thermometer to measure air temperature in the shade (under the table is a good place)

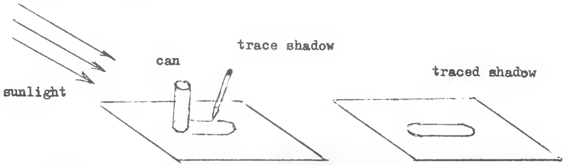


sensing plate horizontal as shown below.

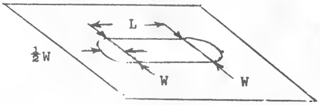


SIMM-1

Record the meter reading and the meter constant with the other data. Now remove one of the cans from the paper plate and set it on a piece of paper to trace its shadow as shown.



After you have finished tracing the shadow, place the can back on the paper plate. You can calculate the surface area of the traced shadow wihtin a few percent by considering it to be made up of two half circles and a rectanglo as shown below.



Measure distances with a ruler carefully

(to .1 cm)

$$\text{Area} = \frac{\pi}{4} W^2 + LW$$

After calculating the shadow area record it with the other data. (Keep the paper with the shadow trace with your other data for reference if needed.) A sample data sheet and data for this experiment can be seen on page E-25. You may want to arrange your data in this manner.

Observe the temperature of the cans about every 20 minutes. When the temperature of the white can has increased at least 5° C and the temperature of the black can has increased at least 15° C (this usually takes an hour to an hour and a half), carefully measure and record the temperatures of both cans along with the time. Now set the black can on a paper plate in the shade. Again measure and record the air temperature, the horizontal solar insolation, and the new shadow area by making another shadow trace using the white can.

Measure the temperature of the black can approximately every 20 minutes. When its temperature has decreased at least 5° C (this may take more than an hour), carefully measure and record its temperature, the time, and also the air temperature. After finishing with these measurements carefully weigh one of the cans (to about a hundredth of a kg) or measure the amount of water present (to about 10 ml) and record.

The absorptivity of an object is defined as

$$\text{absorptivity} = \frac{\text{power absorbed by object}}{\text{power incident on object}} \qquad (1)$$

We can find the inoident power by

$$\text{power incident} = \text{horizontal solar insolation} \times \text{shadow surface area} \qquad (2)$$

Fìnding the power absorbed by the can is a little more complicated, shown by the following:

$$\text{power absorbed} = \text{power being lost} + \text{increase in stored energy per unit time} \qquad (3)$$

The change in stored energy per unit time is given by the following:

$$\text{increase in stored energy per unit time} = mc_p \frac{(T_{c2} - T_{c1})}{\Delta t} \qquad (4)$$

where m is the oan's mass, c_p is the specifio heat, T_c is the can's temperature and Δt is the time it took for the can's temperature to change from T_{c1} to T_{c2}.

The energy being lost is given by

$$\text{power being lost} = uA\ (T_c - T_a) \tag{5}$$

where u is the overall heat transfer coefficient, A is the surface area of the can, T_c is the average temperature of the can over the period and T_a is the average temperature of the air over the period.

We do not know the value of u for the can but it can be easily estimated from our experimental data. During the last part of the experiment the can was placed in the shade and we measured its temperature as it cooled. No power is being absorbed since the can is in the shade and Equation 3 can be simplified and rewritten as

$$\text{power being lost} = \text{decrease in energy per unit time,} \tag{6}$$

or using equations 4 and 5 (note that "increase = - decrease" and $(T_{c2} - T_{c1}) = -(T_{c1} - T_{o2})$)

$$uA\ (T_c - T_a) = mc_p\ \frac{(T_{c1} - T_{c2})}{\Delta t}$$

or

$$u = \frac{1}{A}\ mc_p\ \frac{(T_{c1} - T_{c2})}{\Delta t}\ \frac{1}{T_c - T_a} \tag{7}$$

Now u can be found if m and c_p are known. We will neglect the mass of the empty can itself because it is small compared to the mass of the water in the can. The mass, m, of the can full of water can be estimated by weighing, or measuring the volume of water and multiplying by the density of water.

$$m = \rho V \tag{8}$$

where ρ is the density of water and V is the volume. Values for water are the following:

$$o_p = 4187\ \text{J/kg-}^{o}\text{C}$$

$$\rho = 1.0\ \text{kg/liter}$$

Other useful conversions can be found on page E-46.

Calculation Procedure

In summary then, to compute the absorptivity of the cans follow the steps outlined below (these equations include correct conversions when data are in the specified units).

1 Calculate the average incident power.

$$\begin{pmatrix}\text{average}\\ \text{incident}\\ \text{power}\end{pmatrix} W = \begin{pmatrix}\text{average horizontal}\\ \text{solar insolation}\end{pmatrix} \frac{kW}{m^2} \begin{pmatrix}\text{average shadow}\\ \text{surface area}\end{pmatrix} cm^2 \left(\frac{1}{10}\right) \frac{m^2}{cm^2} \; \frac{W}{kW}$$

The two measurements of insolatin and shadow area are used to compute the averages in the equation above. The factor of 1/10 converts the units of areas and powers at the same time. Can you derive this factor?

2 Calculate the mass of water in the cans. (This step will not be necessary if the cans are weighed.)

$$m\ (kg) = \rho V \ \ x \ \frac{\text{liter}}{1000\ ml}$$

where ρ = 1.0 kg/liter and the volume, V, is in milliliters (ml).

3 Calculate the overall heat transfer coefficient (using the two temperatures and the time interval when the black can is cooling).

$$u\ (W/^{\circ} C\text{-}m^2) = mc_p \frac{(T'_{c1} - T'_{c2})}{\Delta t \times 60\ sec/min} \quad \frac{1}{T'_c - T'_a} \quad \frac{1}{A}$$

where m – mass of water in kg

c_p – 4187 J/kg – $^{\circ}$ C = 4187 W-sec/kg–$^{\circ}$ C

T'_{c1} – initial can temperature when set in the shade in $^{\circ}$ C

T'_{c2} – final can temperature in $^{\circ}$ C

T'_c – average can temperature when the can is cooling in $^{\circ}$ C

T'_a – average air temperature when can is cooling in $^{\circ}$ C

Δt – time the can is in the shade in minutes

A – the surface area of the can in m^2

4 Calculate the absorbed power for both cans (using the temperatures and times for the black and white cans when being heated by the sun).

$$\text{power absorbed (W)} = uA\,(T_c - T_a) + mc_p \frac{(T_{c2} - T_{c1})}{\Delta t \; 60 \text{ sec/min}}$$

where u - value from step 3 in $W/^\circ C - m^2$

m, c_p and A - same as in step 3

T_c - average can temperature when being heated, in $^\circ C$

T_a - average air temperature when the can is being heated, in $^\circ C$

T_{c1} - initial can temperature when set in the sun, in $^\circ C$

T_{c2} - final can temperature when taken out the sun, in $^\circ C$

Δt - time the can is in the sun, in minutes

5 Compute both cans' absorptivity.

$$\text{absorptivity} = \frac{\text{power absorbed}}{\text{power incident}}$$

power absorbed - from step 4 in W

power incident - from step 1 in W

A sample set of calculations follows the data sheet on pages E-25,26. Our experiment gave values of absorptivity for black paint of .90-.98 and for white paint, .25- .35. How do your values compare?

Solar Absorptivity Experiment
July 18, 1978
Bozeman, MT

DATA	Cans placed in sun	Cans moved from sun to shade	End of test
time (hr:min)	11:02	11:58	1:01
air temp ($^\circ$ C)	21	21	21
white can temp ($^\circ$ C)	18	24	
black can temp ($^\circ$ C)	19	34	28.5
horizontal solar insolation (kW/m^2)	.68 x 1.19	.86 x 1.19	
shadow area (cm^2)	103	80	

volume of water – 370 ml

CALCULATIONS

1 Average horizontal insolation $= \dfrac{.68 \times 1.19 \; + \; .86 \times 1.19}{2}$

$$= .92 \ kW/m^2$$

Average shadow area $= \dfrac{103.2 + 80.0}{2} = 92 \ cm^2$

Power incident $= .92\left(\frac{kW}{m^2}\right) 91.6 \left(cm^2\right) \ \frac{1}{10} \ \frac{m^2}{cm^2} \ \frac{W}{kW}$

$$= 8.5 \ W$$

2 $m = 1\left(\frac{kg}{l}\right) 370 \ (ml) \ \frac{1 \ l}{1000 \ ml} = .37 \ kg$

Surface area of can (A) measured as 278 cm^2 or .027 m^2

3 $T'_c = \dfrac{34^\circ \ C + 28.5^\circ \ C}{2} = 31.3^\circ \ C, \quad T'_a = 21^\circ \ C$

Δt = 1:01 pm – 11:58 am = 1 hr. 3 min. = 63 min.

$$u = .37 \ (kg) \ 4187\left(\frac{W\text{-}sec}{kg \ ^\circ C}\right) \frac{(34^\circ \ C - 28.5^\circ \ C)}{63(min)60\left(\frac{sec}{min}\right)} \ \frac{1}{(31.5^\circ C - 21^\circ \ C)} \ \frac{1}{.027 m^2}$$

$$= 7.9 \ W/m^2 - {}^\circ C$$

4 For the black can,

$$T_c = \frac{19^\circ\ C + 34^\circ\ C}{2} = 26.5^\circ\ C\ ,\quad T_a = 21^\circ\ C$$

$$\Delta t = 11{:}58\ \text{am} - 11{:}02\ \text{am} = 56\ \text{min}$$

$$\text{Power being absorbed (W)} = 7.9\left(\frac{W}{m^2\,{}^\circ C}\right) .027\ m^2\ (26.5^\circ - 21^\circ C) + .37\ \text{kg}\ 4187\left(\frac{W\text{-sec}}{\text{kg}\ {}^\circ C}\right)\frac{(34^\circ C - 19^\circ C)}{56\,(\text{min})\,60\left(\frac{\text{sec}}{\text{min}}\right)}$$

$$= 8.1\ W$$

For the white can,

$$T_c = \frac{18 + 24}{2} = 21^\circ\ C$$

T_a and Δt , same as above

$$\text{Power being absorbed (W)} = 7.9\left(\frac{W}{m^2\,{}^\circ C}\right) .027\ m^2\ (21^\circ C - 21^\circ C) + .37\ \text{kg}\ 4187\left(\frac{W\text{-sec}}{\text{kg}\ {}^\circ C}\right)\frac{(24^\circ C - 18^\circ C)}{56\,(\text{min})\,60\left(\frac{\text{sec}}{\text{min}}\right)}$$

$$= 2.8\ W$$

5 For the black can,

$$\text{absorptivity} = \frac{8.1\ W}{8.5\ W} = .95 \text{ or } 95\%$$

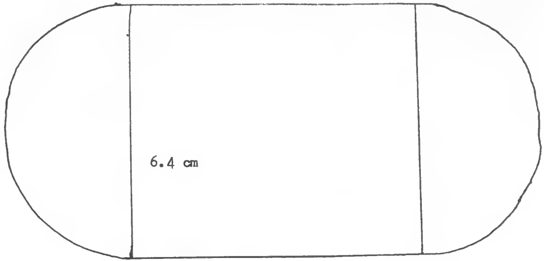
For the white can,

$$\text{absorptivity} = \frac{2.8\ W}{8.5\ W} = .33 \text{ or } 33\%$$

Shadow traces
for
Solar Absorptivity Experiment

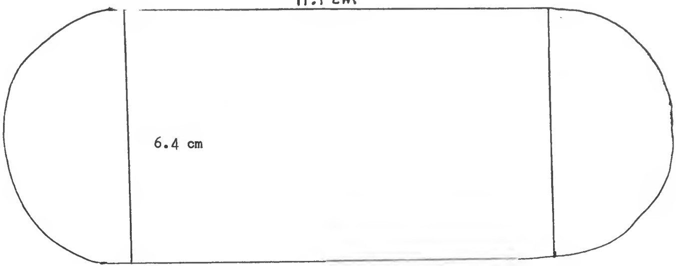
7/18/78

at 11:58



$$A = \frac{\pi}{4}(6.4\ \text{cm})^2 + (7.6\ \text{cm})\ 6.4\ \text{cm} = 80.0\ \text{cm}^2$$

at 11:02



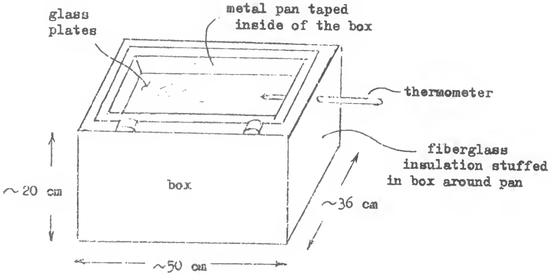
$$A = \frac{\pi}{4}(6.4\ \text{cm})^2 + (11.1\ \text{cm})\ 6.4\ \text{cm} = 103.2\ \text{cm}^2$$

Experiment 8: A Simple Solar Oven

You can make a simple solar air collector from the materials and construction shown below.

Materials

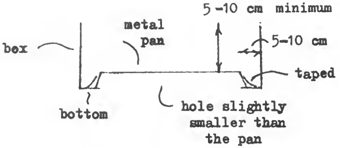
- a couple of cardboard boxes of which one should be approximately 50 cm x 36 cm by 20 cm deep
- one rectangular cake pan, approximately 23 cm x 33 cm by 4-5 cm deep
- 2 plates of .32 cm glass, approximately 25 cm by 36 cm
- a roll of 5 cm wide masking tape
- flat black paint
- a thermometer, 0 to 150° C range or close to this
- fiberglass insulation, about 1 meter of 36 cm wide, 15 cm deep batt
- knife and ruler
- drill and some drill bits
- small piece of aluminum foil



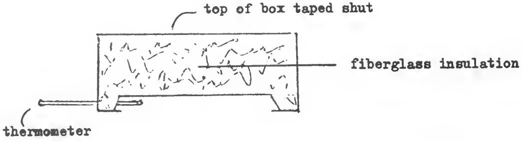
A Simple Solar Oven

Construction

Select a proper size box so that the metal pan can rest on the bottom with 5 or 10 cm between the side of the pan and the side of the box and 5 to 15 cm between the top of the pan and the top of the box. These clearances are necessary to insulate the collector pan to reduce heat loss. Now drill a hole in one side of the pan so that a thermometer may be inserted. Paint the inside of the pan black. Cut a hole in the middle of the box bottom which is slightly smaller than the length and width of the pan and then tape the metal pan over the hole inside the box as shown below.

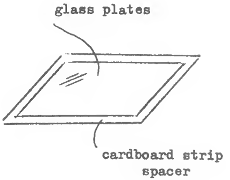


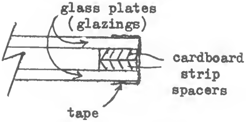
Now punch a hole in the side of the box and insert the thermometer into the pan. Fill the inside of the box with insulation and then close the top of the box and tape it shut as shown below (or make a cardboard cover for the box and tape it over the bottom of the box).



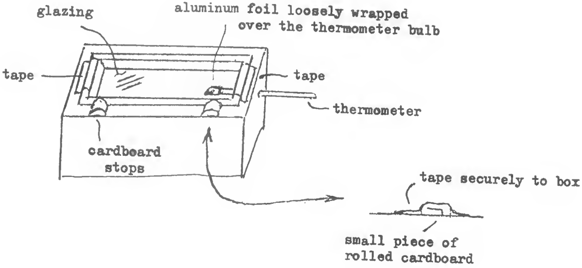
Place either one or two sheets of glass over the absorber pan to complete your solar collector. A double glazing (2 plates of glass) can

be made for the collector in the following manner:





Place the glazing on top of your oven as shown below:



When tilting your oven toward the sun, orient it in such a manner that the cardboard stops will keep the glass from sliding off the box and remember to tape the glass securely. Also, when using your collector, a small piece of aluminum foil should be placed over the thermometer bulb to keep it from receiving direct radiation from the sun (this would give you erroneous readings). Now you are ready to test your oven.

Experiments

Take your oven and place it facing the sun. Note how the temperature rises. What is the maximum temperature you can obtain? Could you boil water or cook food with your collector? You might try cooking some apple slices. (Lay the apple slices on small pieces of tin foil inside the collector.) Compare the maximum temperature obtained when using one glazing to two glazings. Which one is higher and why? You might also test your collector on a cloudy day. Do you get a temperature rise? Explain what happens. (You might try taking a reading of the diffuse solar insolation you are receiving with the SIMM-1 meter, referring to Experiment 3.)

Now that you have built the solar oven you should write down your test results and keep them with the oven. Repeat this test at different times during the year and for different tilt-angles to the sun. Does the oven work better in the winter than in the fall or spring?

Experiment 9: A Simple Water Solar Collector

Using the solar oven from Experiment 8 and the additional materials below, a simple water collector can be constructed. With this arrangement the thermal efficiency of your collector can be determined. The efficiency will show how well you collector collects the sun's energy.

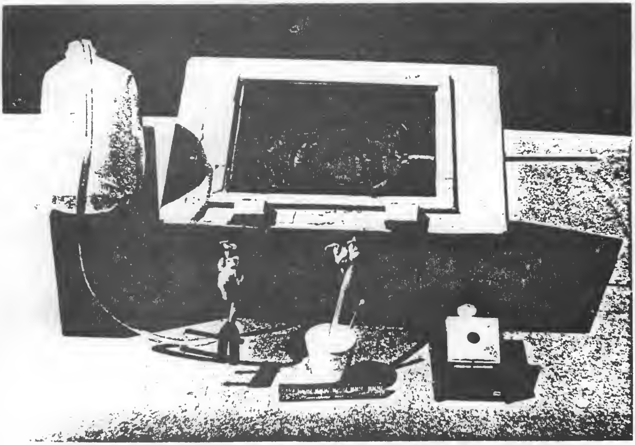
Materials

- solar collector from Experiment 8
- copper tubing, .64 cm diameter, about 5 m long
- flexible plastic tubing, proper size to fit snugly over copper tubing, about 2 m
- C-clamp to squeeze plastic tubing (to oontrol water flow)
- a 4 liter milk jug
- styrofoam cup
- two thermometers, 0-100°C or close to this range
- measuring cup or graduated cylinder
- fiberglass insulation (small amount)
- flat black paint
- some tin or aluminum foil
- SIMM-1 solar radiation meter
- watch which reads to minutes and seconds
- a drill and some drill bits
- calculator and ruler

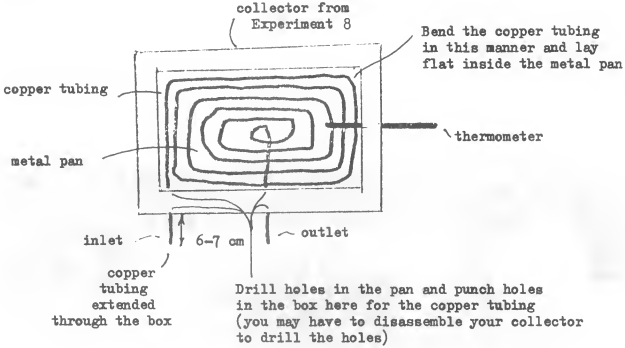
In experiment 8 we learned that the air space inside the solar oven reached a high equilibrium temperature. In this experiment we will attempt to remove heat from the air space within the oven and thus create a true solar collector.

We will remove the heat by placing a coil of copper tubing in the air space. Water is then forced through the tubing and the water absorbs some heat from the "oven" as it passes through. An engineer would call this coil of tubing a "heat exchanger".

A commercially-built solar collector would probably use a more efficient (and more complex) heat exchanger. Our copper tube heat exchanger is used for this experiment because it is easy to obtain and fabricate.

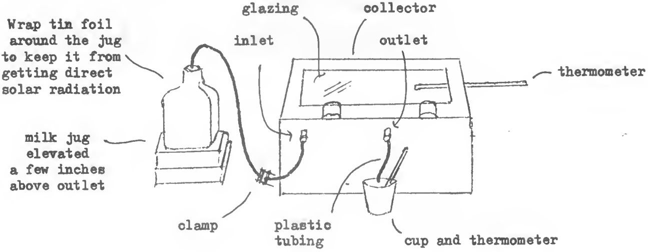


Apparatus for Solar Collector Test



A Water Solar Collector

Arrange your solar collector system in the manner shown in the figures. The picture of the collector used in the sample experiment is shown on page E-33 and may be helpful.



The water flows through the system by gravity or syphoning so the jug must be elevated a few inches above the outlet. To start the water circulating put your mouth over the milk jug and blow lightly. Water should begin flowing through the collector in a few seconds. Do not suck on the outlet tubing to start the collector, as out in the sun the copper tubing can quickly become hot enough to create steam which blows out the outlet tube. Use the clamp to control the water flow rate. The water must flow slowly to get a noticeable temperature rise between the inlet and the outlet. A flow rate whioh fills a small cup in one to two minutes should be satisfactory.

Try putting your new water collector out in the sun without the water oirculating and let it set for a few minutes until the pan temperature reaches a maximum. Now start the water circulating (CAREFUL: steam may come out the outlet tube on a clear warm day.) How much does the pan temperature drop? Is the heat exchanger working?

You can calculate the efficiency of your collector by the following procedure. Your collector must be at thermal equilibrium, i.e., inlet and outlet temperatures should be constant. You may want to run one jug of water through the collector to establish equilibrium and set the flow rate. Face your collector directly at the sun and use water which is close to the same temperature as the air. Adjust the clamp so that the water flows slowly enough that there is at least a 5° C temperature increase between inlet and outlet temperatures. Measure the inlet temperature by inserting the thermometer in the jug. Lightly stir the water in the jug before measuring. The outlet temperature is measured from the water collected in the styrofoam cup.

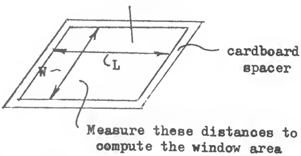
The following data will have to be recorded to compute the efficiency:

water inlet temperature
water outlet temperature
solar insolation
water flow rate
collector window area

Data may be arranged as shown on the sample data sheet on page E-38. Measure the water temperatures as discussed earlier. Use the SIMM-1 to

measure the solar insolation. The plate of the meter should be in the same plane as the collector. Remember to record the meter reading and meter calibration constant. The water flow rate can be obtained by measuring the volume of the styrofoam cup and then recording the time it takes to fill the cup. The flow rate should be measured at the same time the other readings are being taken as there will be a slight decrease in the flow rate as the level in the jug drops.

Area = L x W



You may want to make several sets of readings for your collector and then calculate efficiencies for each set of data and see how they compare. Taking an average of all the tests will help eliminate experimental error.

The efficiency of the collector is defined as

$$\text{efficiency} = \frac{\text{power being collected in water}}{\text{solar power incident on collector}}$$

The power incident is calculated by the following:

power incident = solar insolation x collector window area

The power being collected can be computed by the following:

power collected = (water flow rate) (energy gained/unit water)

or

$$\text{power collected} = \dot{V}\left(\frac{l}{sec}\right) \rho \left(\frac{kg}{l}\right) c_p \left(\frac{W\text{-}sec}{kg\ {}^\circ C}\right) \Delta T\ ({}^\circ C)$$

where ΔT is the temperature change through the collector, c_p is the water's specific heat, $\dot{V}$ is the water flow rate and ρ is the density of water.

To summarize, the efficiency can be computed using the following steps (these equations contain correct conversions when data is in the specified units):

1 Calculate the incident power.

$$\text{incident power} = \text{solar insolation}\left(\frac{kW}{m^2}\right)\ \text{collector window area}\ (cm^2)\ \frac{1}{10}\ \frac{m^2}{cm^2}\ \frac{W}{kW}$$

2 Calculate the water volume flow rate.

$$\dot{V}\ (ml/sec) = \frac{\text{volume of water (ml)}}{\text{time to fill volume (sec)}}$$

3 Calculate the power being collected using

$$\text{power being collected}\ (W) = \dot{V}\left(\frac{ml}{sec}\right)\ \rho\left(\frac{kg}{ml}\right)\ c_p\left(\frac{W\text{-}sec}{kg\ ^\circ C}\right)\ \Delta T\ (^\circ C)\ \frac{1}{1000}\left(\frac{liters}{ml}\right)$$

where T = outlet temperature ($^\circ$ C)– inlet temperature ($^\circ$ C)

c_p = 4187 J/kg-$^\circ$ C or 4187 $\frac{W\text{-}sec}{kg\ ^\circ C}$

$\dot{V}$ – in ml/sec

ρ = 1.0 kg/liter

4 Calculate efficiency.

$$\%\ \text{efficiency} = \frac{\text{power being collected (W)}}{\text{power incident (W)}} \times 100$$

A sample set of calculations can be seen on page E-38. Typical efficiencies for a water collector operating under these conditions of bright sun and warm air temperatures range from about 60 to 80%. In the winter with bright sun and cold ambient air temperatures the efficiency of a collector may only be 15-40% due to the increased heat losses.

How much power actually penetrates the glass glazing of your collector? Determine this by measuring the solar insolation behind the glazing with the SIMM-1 radiation meter. You can also determine the transmissivity of the glazing using the equation

$$\text{transmissivity} = \frac{\text{power transmitted by glass}}{\text{power incident on glass}}$$

SAMPLE EXPERIMENT

Water Collector Efficiency

July 18, 1978

Bozeman, MT

DATA

run	1	2	3
inlet water temperature ($^\circ$ C)	16	17	21
discharge water temperature ($^\circ$ C)	22	24	29
collector temperature ($^\circ$ C)	44	45	51
solar insolation (kW/m^2)	.88 x 1.19	.87 x 1.19	.87 x 1.19
flow rate			
volume (ml)	185	185	185
time interval (min:sec)	1:15	1:30	1:35

Collector window area

width = 22.9 cm

length = 33.0 cm

area = 755 cm^2

Ambient air temperature: 22° C

SAMPLE CALCULATIONS

1 Power incident $= (.88 \times 1.19)\left(\frac{kW}{m^2}\right) 755\,(cm^2)\ \frac{1}{10}\left(\frac{m^2}{cm^2}\ \frac{W}{kW}\right)$

$= 79\ W$

2 Time to fill volume = 1:15 = 75 sec

Water flow rate $= \frac{185\,(ml)}{75\,(sec)} = 2.5$ ml/sec

3 $\triangle T = 22^\circ\ C - 16^\circ\ C = 6^\circ\ C$

Power being collected $= 2.5\left(\frac{ml}{sec}\right)\frac{1}{1000}\left(\frac{liter}{ml}\right) 1\left(\frac{kg}{l}\right) 4187\left(\frac{W\text{-}sec}{^\circ C\ \ kg}\right) 6\,(^\circ C)$

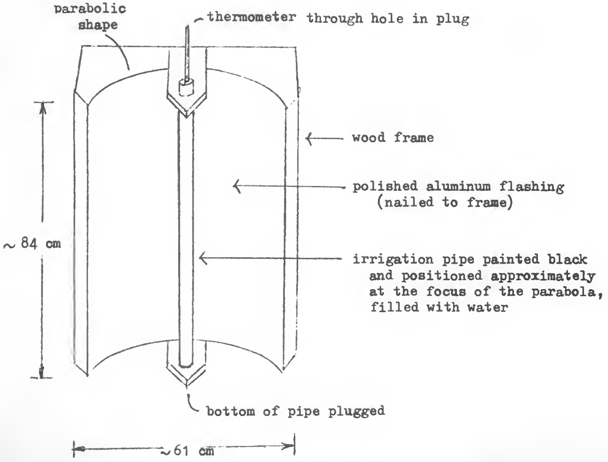
4 Efficiency $= \frac{62}{79} \times 100 = 78\%$

Experiment 10: A Solar Concentrating Collector

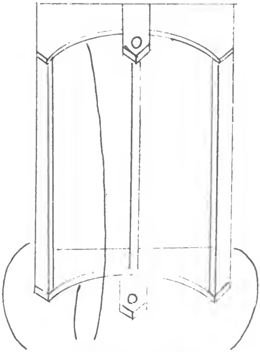
With a little time, patience and expense a workable solar concentrating collector can be constructed. The figure below and the photograph on page E 44 depict a collector we built for the sample experiment.

Materials

- assorted power and hand tools (see drawing below and on the following page)
- 1.3 cm plywood or particle board and some wood scraps (estimate amount from figure 1)
- aluminum flashing, about 1 m x .5 m
- aluminum irrigation pipe, approximately 5 cm diameter and 3 m long
- nails
- thermometer, 0–100° C or close to this range
- flat black paint

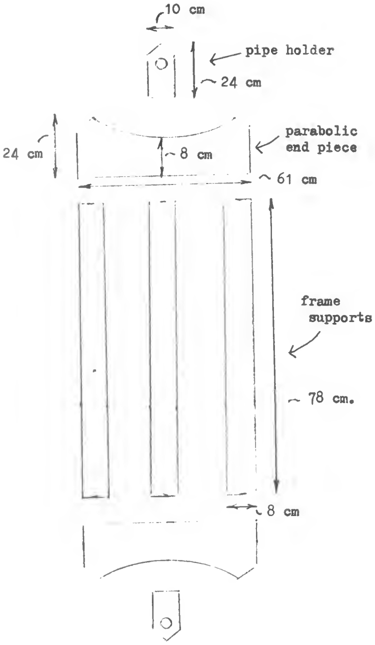


A Solar Concentrating Collector



Edge of flashing is nailed to these pieces

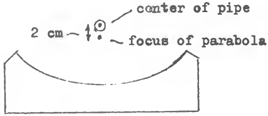
Pieces of the wood frame are nailed together



Details of the wood frame

Dimensions are shown to give an idea of the sizes needed. Building to these dimensions is not required.

Frame supports are positioned so that one support is fastened to the middle of the parabolic end pieces and the other two spaced equal distance from the middle, so the edge of the flashing can be nailed to them. The pipe holders are fastened so that the center of the pipe is about 2 cm past the focus of the parabola as shown below.



The irrigation pipe is painted black and plugged at one end while the other end is left open to add water. A thermometer is inserted in the open end through a hole in a loose-fftting plug. Be careful not to seal both ends of the pipe as this might result in a bursting of the pipe if the water inside begins to boil when in the sun. The aluminum flashing works <u>much</u> better if it is polished. This can be done by hand or with the use of a power buffer and a suitable buffing compound. The more reflective the surface the better the collector will function.

The parabolic end pieces can be made in the manner illustrated in Figure 2. Select a proper size board and draw a base line 8 or 9 cm from one end. A nail centered on the board and 10 or 11 cm from the base line will be the focus of the parabola. A carpenter's square or a square board is used to construct the parabola.

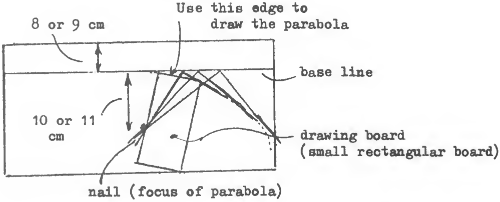


Figure 2: Drawing a parabola

Hold one corner of the drawing board against the baseline and the side of the drawing board against the nail. Make a line along the edge of the drawing board. Then rotate the drawing board a small angle and make another line always keeping the corner of the drawing board on the basline and the side of the board against the nail. After many rotations a parabola will take shape inside the tangent lines you have drawn. Draw a parabola large enough so that the width of the aluminum flashing will fit along the parabola's length.

After constructing your collector, place it out in the sun. Check the location of the focus of your concentrator by holding a small piece of white paper along the side of the irrigation pipe between the pipe and the flashing. A bright line about 2 cm wide should be seen on the paper. You might need to change the position of the irrigation pipe slightly if the light is not focusing correctly on the pipe. Remember, though, the collector should be facing directly at the sun to focus correctly.

Next, fill the irrigation pipe with water and see what maximum temperature you can obtain. Does your collector get hot enough to boil water? Hot enough to make soup, wash dishes or take a bath?

The efficiency of the collector can be computed using the following procedure and additional materials.

Additional Materials

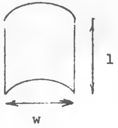
- SIMM-1
- watch, to read hours and minutes
- measuring cup or graduated cylinder

Place the collector directly facing the sun and record the following data:

time
solar insolation
temperature of water in tube

The solar insolation measured will be a maximum value with the sensing plate of the SIMM-1 facing directly at the sun, the same plane as the solar collector. After the temperature of the collector has risen at least 5 °C, measure and record the data once more. You may want to record

several sets of data so that you can compute the efficiency of your collector as its temperature increases. Remember to keep the collector facing directly at the sun. Next measure and record the collector window area as shown below and the amount of water in the irrigation pipe.



Area = wl

Data may be arranged as shown on the sample data sheet on page E-45.

Use the following equations to compute the collector efficiency:

1 Incident power (W) = $\text{solar insolation} \left(\frac{kW}{m^2}\right)$ collector area (cm^2) $\frac{1}{10}\left(\frac{m^2}{cm^2}\ \frac{W}{kW}\right)$

Solar insolation is average value over the collection period in kw/m^2.

2 Mass of water (kg) = volume (liters) density $\left(\frac{kg}{liter}\right)$

Density = 1.0 kg/liter

3 **Power collected per unit time** (W) = $m\ (kg)\ c_p \left(\frac{W\text{-}sec}{kg\ {}^{o}C}\right) \frac{\Delta T}{\Delta t} \left(\frac{{}^{o}C}{sec}\right)$

where m - mass of water in kg

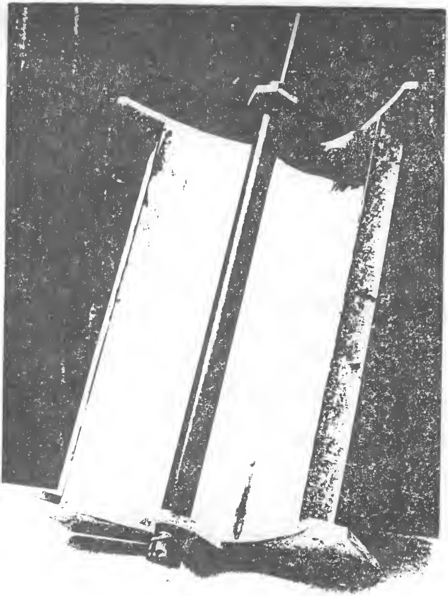
c_p - specific heat of water = 4187(J/kg- °C)= 4187 $\left(\frac{W\text{-}sec}{kg\ {}^{o}C}\right)$

ΔT - change in temperature of collector in °C

Δt - collection period in seconds
(power absorbed by the pipe container is small and hence neglected)

4 Efficiency = $\frac{\text{energy collected per unit time}}{\text{energy incident per unit time}} \times 100$

A sample calculation of efficiency can be seen on page E45. Try calculating the efficiency of your collector for different collector temperatures. What happens to the efficiency as the collector reaches higher temperatures? Can you explain this change?



Parabolic solar concentrating collector

SAMPLE EXPERIMENT

Concentrating Collector Efficiency

July 19, 1978

Bozeman, MT

DATA

time (hour:min)	10:48	11:19	11:35
solar insolation (kW/m^2)	.94 x 1.19	.92 x 1.19	.95 x 1.19
collector temperature (^oC)	31 ^oC	65 ^oC	75 ^oC

water volume = 1.48 liters

collector area = 82.6 (cm) 44.5 (cm) = 3680 cm^2

ambient air temperature = 22 ^oC

CALCULATIONS (for first collection period)

1 Average solar insolation = $\dfrac{(.94 \times 1.19)\,\frac{kW}{m^2} + (.92 \times 1.19)\,\frac{kW}{m^2}}{2}$

$= 1.11 \ kW/m^2$

Power incident = $1.11 \left(\frac{kW}{m^2}\right) 3680\,(cm^2)\,\frac{1}{10} \ \frac{m^2}{cm^2}\,\frac{W}{kW}$

$= 408 \ W$

2 Mass of water = $1.48\ (l)\ 1.0 \left(\frac{kg}{l}\right) = 1.48\ kg$

3 $\Delta T = 65\ ^oC - 31\ ^oC = 34\ ^oC$

$\Delta t = 11{:}19 - 10{:}48 = 31$ min $\quad$ $31 \text{ min } 60 \left(\frac{sec}{min}\right) = 1860\ (sec)$

Power collected = $1.48\ (kg)\,4187 \left(\frac{W\text{-}sec}{kg\ ^oC}\right) \frac{34}{1860} \left(\frac{^oC}{sec}\right)$

$= 113\ W$

4 Efficiency = $\frac{113}{408} \times 100 = 28\ \%$

Some Useful Conversions

Length

$1 \text{ in} = 2.540 \text{ cm}$

$1 \text{ ft} = .3048 \text{ m}$

Area

$1 \text{ in}^2 = 6.450 \text{ cm}^2$

$1 \text{ ft}^2 = 9.290 \times 10^{-2} \text{ m}^2$

Volume

$1 \text{ in}^3 = 16.39 \text{ cm}^3 = 16.39 \text{ ml}$

$1 \text{ ft}^3 = 2.832 \times 10^{-2} \text{ m}^3 = 28.32 \text{ liters}$

$1 \text{ oz} = 29.57 \text{ ml} = 29.57 \text{ cm}^3$

$1 \text{ gal} = 3.785 \text{ liters} = 3.785 \times 10^{-3} \text{ m}^3$

Mass

$1 \text{ ounce (mass)} = 2.834 \times 10^{-2} \text{ kg}$

$1 \text{ pound} = .4536 \text{ kg}$

Energy

1 foot-pound-force (ft-lbs) = 1.356 Joule

$1 \text{ BTU} = 1.055 \times 10^3 \text{ Joule}$

1 kW-hr = 3412 BTU = 3600 Joule

Power

1 Watt = 1 Joule/sec

1 BTU/hr = .293 Watt

Temperature

$T_C = 5/9 \, (T_F - 32)$

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THE MOTHER EARTH NEWS. The Mother Earth News, Inc., 105 Stoney Mountain Road, Hendersonville, NC 28739, Bi-monthly, $10.00/yr

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